
Forwarding and Network Paradigms

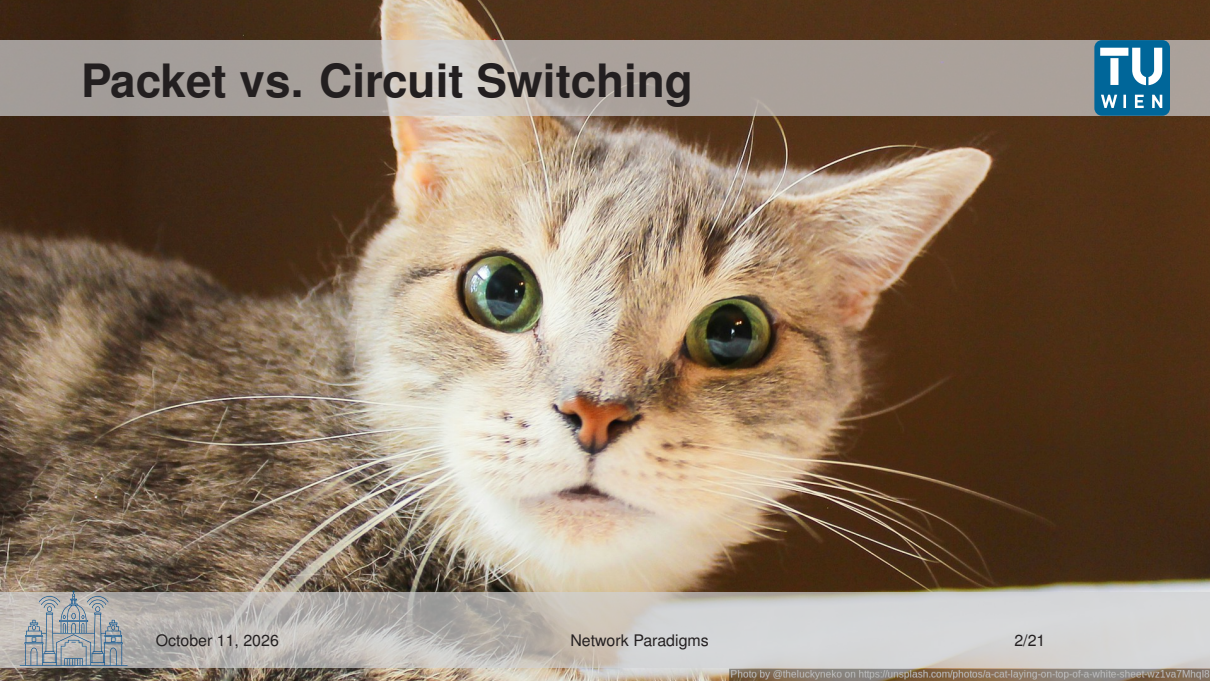
Circuit, packet switched, state

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A thick, solid blue vertical bar is positioned on the right side of the slide, extending from the top of the main content area to the bottom.

Packet vs. Circuit Switching



October 11, 2026

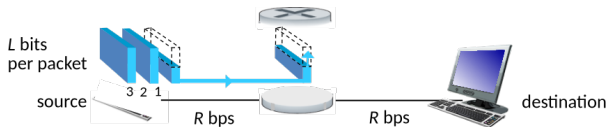
Network Paradigms

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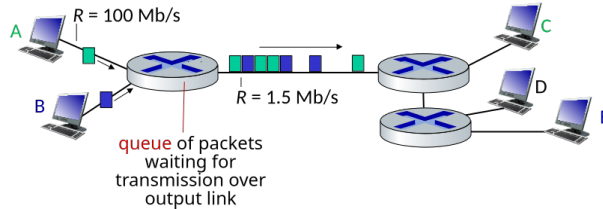
Photo by @theluckyneko on <https://unsplash.com/photos/a-cat-laying-on-top-of-a-white-sheet-wz1va7Mhqj8>

Packet-switching: Store-and-forward

- **Packet transmission delay:** takes L/R seconds to transmit (push out) L -bit packet into link at R bps
- **Store-and-forward:** entire packet must arrive at router before it can be transmitted on next link end-to-end delay $= 2 * L/R$ (assuming zero propagation delay)



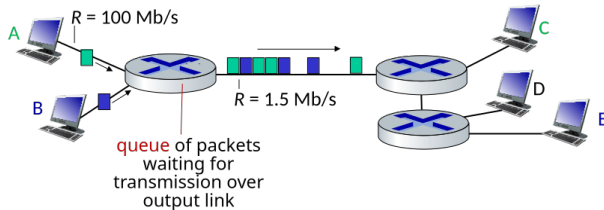
Packet-switching: Queuing



- **Queuing** occurs when work arrives faster than it can be serviced



Packet-switching: Queuing



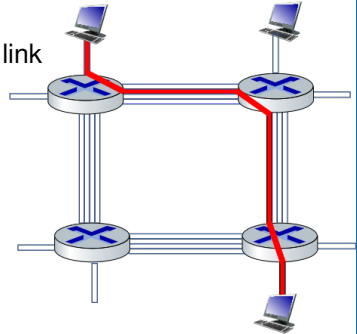
- **Packet queuing and loss:** If arrival rate (in bps) to link exceeds transmission rate (bps) of link for some period of time:
 - Packets will queue, waiting to be transmitted on output link
 - Packets can be dropped (lost) if memory (buffer) in router fills up



Alternative: Circuit-Switching

End-to-end resources allocated to, reserved for “call” between source and destination

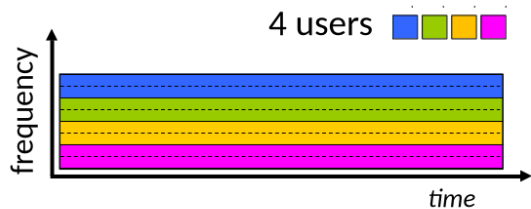
- In the diagram, each link has four circuits
 - Call gets 2nd circuit in top link and 1st circuit in right link
- Dedicated resources: no sharing
 - Circuit-like (guaranteed) performance
- Circuit segment idle if not used by call (no sharing!)
- Commonly used in traditional telephone networks



Circuit-Switching: FDM and TDM

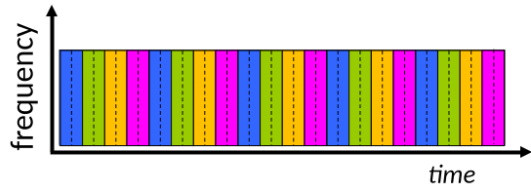
Frequency Division Multiplexing

- Optical, electromagnetic frequencies divided into (narrow) frequency bands
- Each call allocated to its own band, can transmit at band's max rate



Time Division Multiplexing

- Time divided into slots
- Each call allocated periodic slot(s), can transmit at maximum rate of (wider) frequency band (only) during its time slot(s)



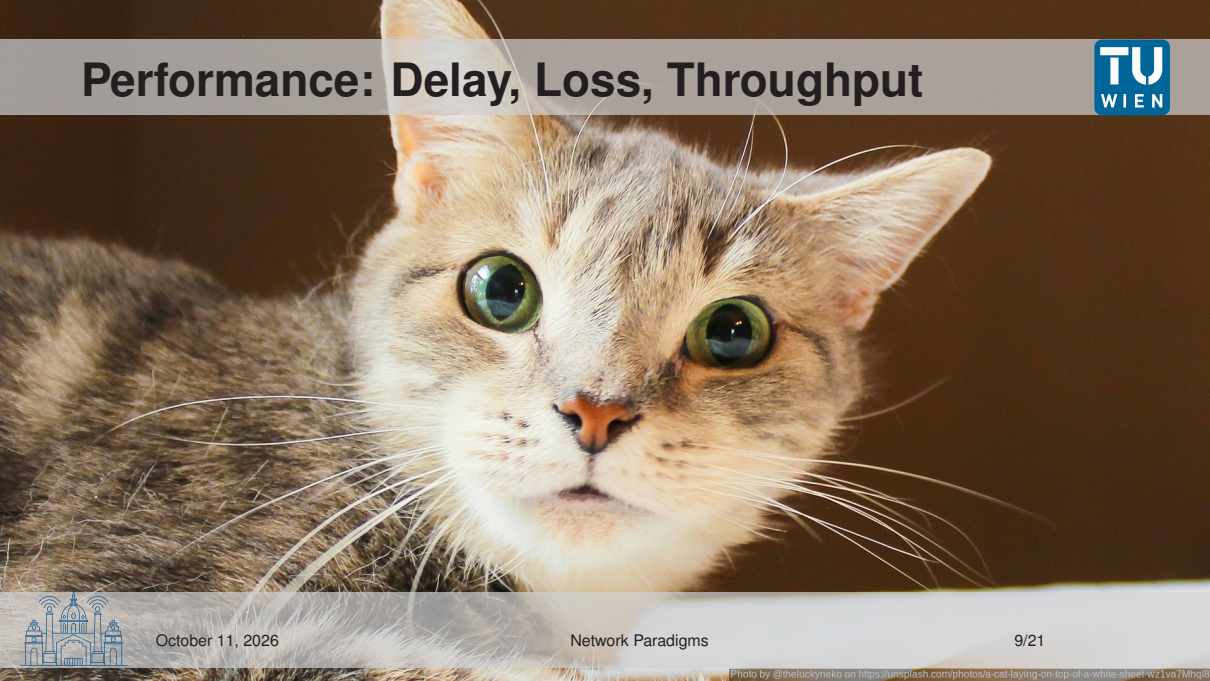
Packet-Switching vs. Circuit-Switching

Is packet-switching a “slam dunk winner”?

- Great for “bursty” data – sometimes has data to send, but not always
 - Resource sharing
 - Simpler, no call setup
- **Excessive congestion possible:** Packet delays/losses due to buffer overflow
 - Protocols needed for reliable data transfer, congestion control



Performance: Delay, Loss, Throughput



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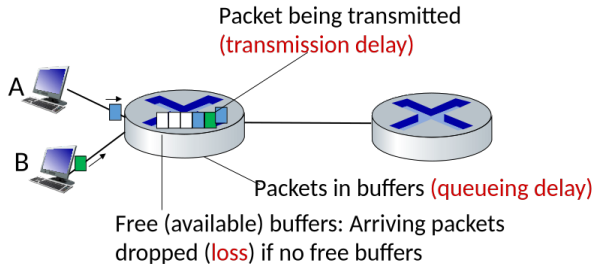
Network Paradigms

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Photo by @theluckyneko on <https://unsplash.com/photos/a-cat-laying-on-top-of-a-white-sheet-wz1va7Mhqj8>

How packet delay & loss occur

- Packets **queue** in router buffers, waiting for turn of transmission
 - Queue length grows when arrival rate to link (temporarily) exceeds output link capacity
- Packet **loss** occurs when memory to hold queued packets fills up



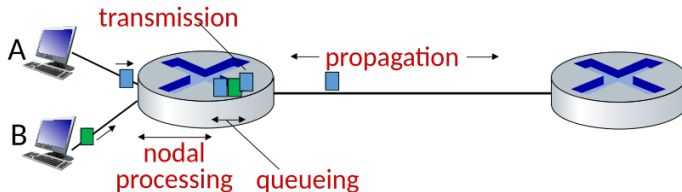
Packet delay: Four components

- d_{proc} : Nodal processing

- Check bit errors
- Determine output link
- Takes typically sub-microseconds

- d_{queue} : Queuing delay

- Time waiting at output link for transmission
- Depends on congestion level of link



$$d_{total} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$



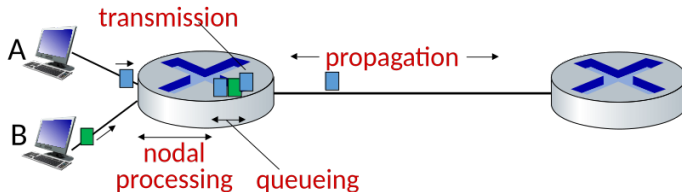
Packet delay: Four components

- d_{trans} : Transmission delay

- L: length of packet (bits)
- R: Link transmission rate (bps)
- $d_{trans} = L/R$

- d_{prop} : Propagation delay

- d: Length of physical link
- s: Propagation speed
($\sim 2 * 10^8 m/sec$)
- $d_{prop} = d/s$



$$d_{total} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

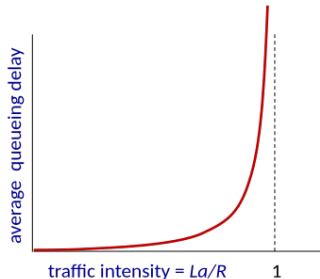


Packet Queuing Delay

- a : Average packet arrival time
- L : Packets length (bits)
- R : Link bandwidth (bit transmission rate)

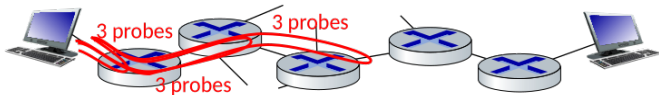
$$\frac{L * a}{R} : \frac{\text{Arrival rate of bits}}{\text{Service rate of bits}}$$

- $L * a/R \sim 0$: avg. queuing delay small
- $L * a/R \sim 1$: avg. queuing delay large
- $L * a/R > 1$: more “work” arriving than can be served! Infinite avg. queuing delay!



“Real” Internet Delays and Routes

- What do “real” Internet delay & loss look like?
- Traceroute program: Provides delay measurement from source to router along end-end Internet path towards destination. For all i :
 - Sends three packets that will reach router i on path towards destination (with time-to-live field value of i)
 - Router i will return packets to sender
 - Sender measures time interval between transmission and reply



“Real” Internet Delays and Routes

Traceroute: rincewind.home.aperture-labs.org to teaching-mail01.vie01.internet.wien

My traceroute [v0.96]

rincewind (2a06:d1c1:a:0:195:191:197:197) -> teaching-mail01.vie01.internet.wien (2a0b:d81:2026-10-11T22:31:47+0200)
Keys: Help Display mode Restart statistics Order of fields quit

Host	Packets		Pings				
	Loss%	Snt	Last	Avg	Best	Wrst	StDev
1. eth0-25.gw01.vie01.as59645.net (2a06:d1c1:a::1)	0.0%	27	0.5	0.5	0.2	0.5	0.1
2. wg0.gw03.ber01.as59645.net (2a06:d1c0::dead:beef:1d01)	0.0%	27	25.1	26.1	24.2	39.9	3.0
3. xe-0-0-13-42.gw01.ber01.as59645.net (2a06:d1c0::dead:beef:1501)	0.0%	27	25.0	25.7	24.3	30.8	1.4
4. xe-0-0-12-2412.gw01.dus01.as59645.net (2a06:d1c0::dead:beef:401)	0.0%	27	33.6	34.2	32.3	48.5	3.2
5. gw01.dus01.internet.wien (2a06:d1c0::dead:beef:7002)	0.0%	27	33.2	33.5	32.7	35.3	0.6
6. gre0.gw01.trtl01.internet.wien (2a0b:d80:1:1::2)	0.0%	27	54.3	55.2	53.6	68.5	2.8
7. xe-0-1-0-2401.gw01.vie01.internet.wien (2a0b:d80:1:3::6004:1)	0.0%	26	54.5	55.7	53.8	69.6	3.2
8. lo0.nfs02.vie01.internet.wien (2a0b:d80:0:1000::656:12)	0.0%	26	54.3	54.8	53.6	56.5	0.7
9. vio0.gw04.vie01.internet.wien (2a0b:d80:0:1012::2)	0.0%	26	55.5	55.4	53.9	60.8	1.3
10. teaching-mail01.vie01.internet.wien (2a0b:d81::be24:11ff:fe97:b680)	0.0%	26	55.5	57.2	55.0	61.1	1.5



“Real” Internet Delays and Routes

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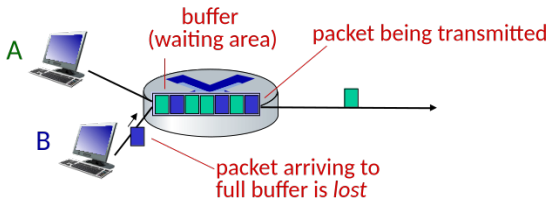
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Keys: Help Display mode Restart statistics Order of fields quit

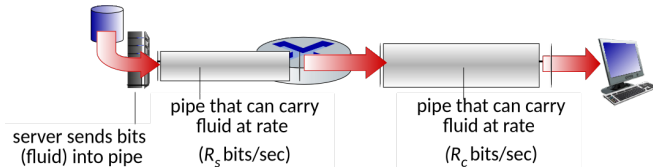
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2. wg0.gw03.ber01.as59645.net (2a06:d1c0::dead:beef:1d01)	0.0%	27	25.1	26.1	24.2	39.9	3.0
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4. xe-0-0-12-2412.gw01.ber01.as59645.net (2a06:d1c0::dead:beef:1401)	0.0%	27	22.6	24.2	22.2	48.5	2.9
Try out “traceroute” (or “mtr”) with different destinations yourself!							
8. lo0.nfs02.vie01.internet.wien (2a0b:d80:0:1000::656:12)	0.0%	26	54.3	54.8	53.6	56.5	0.7
9. vio0.gw04.vie01.internet.wien (2a0b:d80:0:1012::2)	0.0%	26	55.5	55.4	53.9	60.8	1.3
10. teaching-mail01.vie01.internet.wien (2a0b:d81::be24:11ff:fe97:b680)	0.0%	26	55.5	57.2	55.0	61.1	1.5



- Queue (a.k.a. “buffer”) preceding output link has finite capacity
- Packet arriving at full queue is dropped, “lost”
- Lost packet may be retransmitted by previous node, by source end system, or not at all

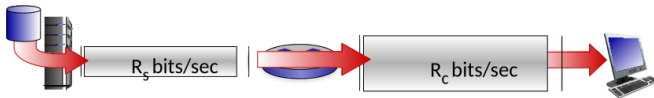


- **Throughput:** Rate (bits/time unit) at which bits are being sent from sender to receiver
- **Instantaneous:** Rate at given point in time
- **Average:** Rate over longer period of time system, or not at all

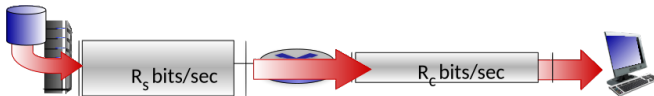


Throughput

- $R_s < R_c$: What is the average end-to-end throughput?



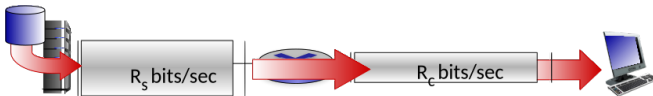
- $R_s > R_c$: What is the average end-to-end throughput?



- $R_s < R_c$: What is the average end-to-end throughput?



Bottleneck link: Link on the end-to-end path that constraints end-to-end throughput.

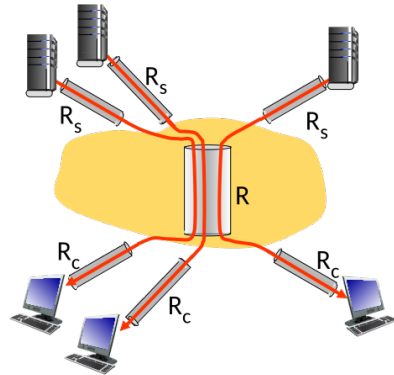


Throughput: A Network Scenario

- Per-connection end-to-end throughput:

$$\min(R_C, R_S, R/10)$$

- In practice: R_C or R_S is often bottleneck



10 connections (fairly) share
backbone bottleneck link R bits/sec

