Tutorial 4:
Transport Layer

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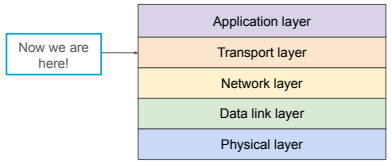
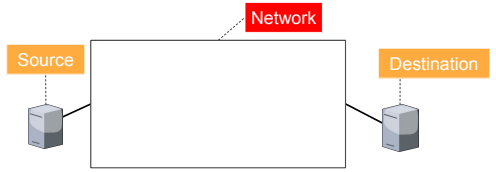
Computer Networks 2025-2026

Where Are We Now?



Recap - Why Transport Layer?



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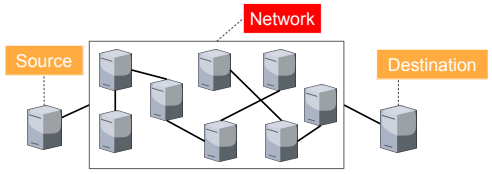
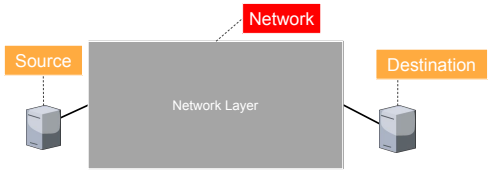
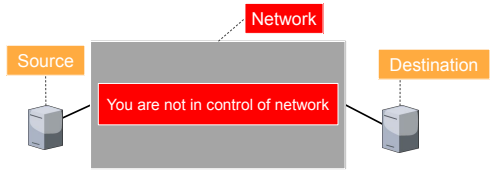


Recap - Why Transport Layer?

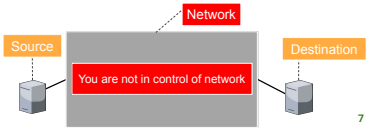


Recap - Why Transport Layer?



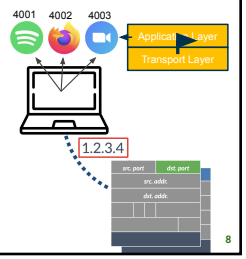
Recap - Why Transport Layer?

You do not know if:
1. Data will be lost
2. Data will be damaged
3. What is network maximum capacity



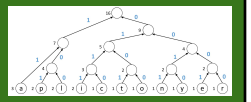
Recap – Port Numbers

- We have **one** end host, but **multiple** applications.
- All applications are running on the **same** IP address.
- Different applications run on different **ports**.
- Each **segment** has a **source** and **destination** port number.



Menu Of The Day

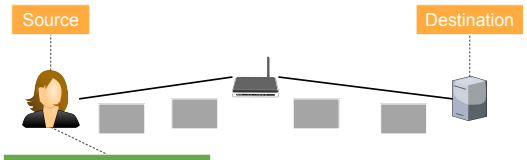
1. Transport Layer
   a. Sequence Numbers
   b. Fast Retransmission
   c. Congestion Control
2. Application Layer Encodings
   a. Base64 Encoding
   b. Huffman Encoding



Recap - Sequence Numbers

Recap - Sequence Numbers

Available Sequence Numbers: {0, 1}



Recap - Sequence Numbers

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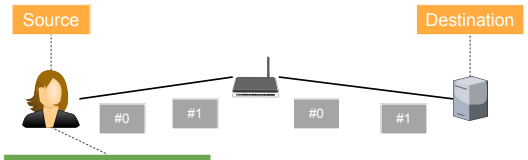

Recap - Sequence Numbers

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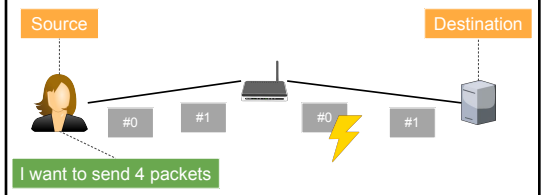
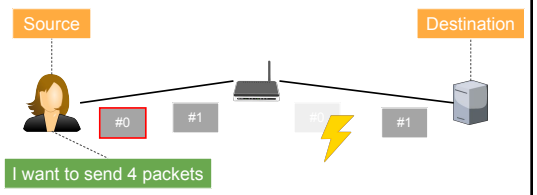


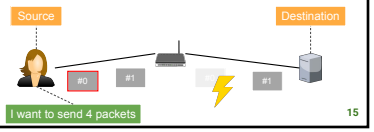
Recap - Sequence Numbers

Available Sequence Numbers: {0, 1}



Recap - Sequence Numbers

- There should **not** be two different packets on the network with the same sequence number (SN)
- After segment lifetime it is safe to reuse sequence numbers



Exercise 1 - World Wrapping Record

In a network with a maximum segment lifetime of **128 seconds**, and a TCP CN protocol that uses **32-bit** sequence numbers **for each byte**, how long does it take for all sequence numbers (SN) to be used when downloading data at a rate of **64 MiB/s**?

Solution - World Wrapping Record

Setup:
- Sequence Numbers (SN): 32 bits
- Download rate: 64 MiB/s
- SN per byte

- SN Range $= 2^{32}$
- Total no. of bytes in segment lifetime $=$ SN Range $= 2^{32}$
- Time to use up all $= \frac{\text{SN Range}}{\text{Download rate in Bytes}} = \frac{2^{32}}{2^{20} \times 2^{6}} = \frac{2^{3}}{2^{2}} = 4 = 64$ seconds

$1\text{MiB} = 2^{20}\text{bytes}$

Answer: 64 seconds

Exercise 2 - Too Fast To Count

In a network with a maximum segment lifetime of **32 seconds**, and a TCP CN protocol that uses **16-bit sequence numbers for each segment**, and has a maximum segment size of **1024 bytes**, what is the maximum mean data rate per connection?

Answer - Too Fast To Count

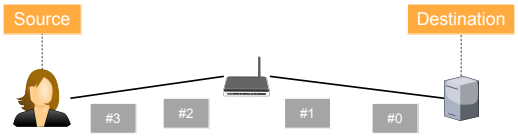
- SN Range = 2^{16}
- Total no. of segments in segment lifetime = SN Range = 2^{16}

Setup:
- SN size: 16 bits
- Max segment size: 1024 bytes
- Segment lifetime: 32 seconds
- SN per segment

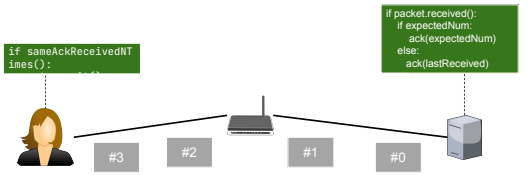
- Max. amount of data you can transmit in segment lifetime = SN Range × Max. segment size
  $= 2^{16} \times 1024 = 2^{16} \times 2^{10} = 2^{26} = \mathbf{64\ MiB}$
- Max. Data Rate $= \frac{\text{max. amount of data you can transmit in segment lifetime}}{\text{segment lifetime}}$
  $= \frac{64\ \text{MiB}}{32\ \text{seconds}} = \mathbf{2\ MiB/s}$

Answer: 2 MiB / s

Recap – Fast Retransmission (FR)

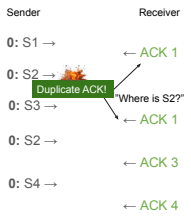


Recap – Fast Retransmission (FR)



Example – Fast Retransmission (FR)

Transmit segments 1 to 4:
- Segment 2 (1st try) - lost
- Segment 2 (2nd try) - received
- FR - upon receiving duplicate acknowledgement twice.
- Receiver buffers packets



Exercise 3 – Fast Retransmission (FR)

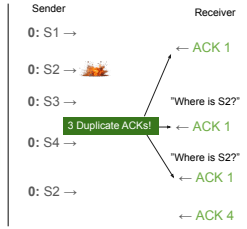
Two hosts are communicating using a TCP CN protocol that uses **fast retransmission** by retransmitting segments when receiving **three** duplicate acks.

Host A transmits segments S1, S2, S3, S4 in order. Segment S2 is lost and S1, S3, S4 are transmitted successfully.

Assume all acknowledgements are transmitted successfully. Model the transmission behaviour.

Solution – Fast Retransmission (FR)

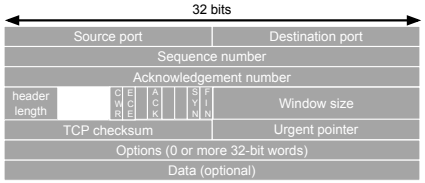
Setup:
- Retransmit upon 3 duplicate ACKs.
- Segments: S1, S2, S3, S4
- Lost Segments: S2



Congestion Control

Recap – TCP Congestion Control

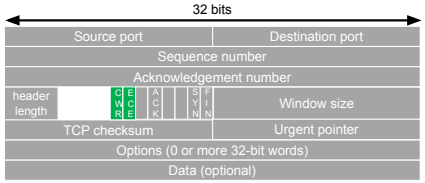
Problem! We do not know the maximum network capacity!



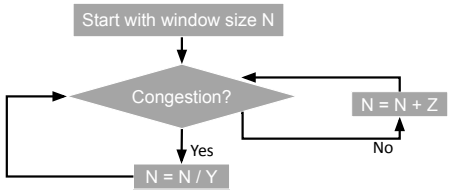
Recap – TCP Congestion Control

Problem! We do not know the maximum network capacity!

But we do know whether its congested!



Recap – Additive Increase and Multiplicative Decrease

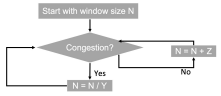


Exercise 4 – TCP CN (AIMD)

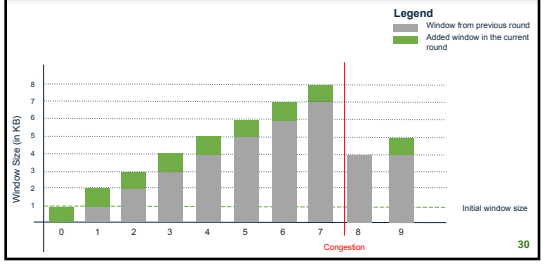
An application is sending data using **TCP CN (additive increase, multiplicative decrease (AIMD))** with the following configurations:

1. The **initial** window size is **1 KB.**
2. Additive increase **adds 1 KB** to the window size every round.
3. Multiplicative decrease **divides** window size by **2**.

The **congestion** is detected after **round 7**. Model the window size round by round **up to round 9 including**. Start with **round 0** being initial window size and round 1 is the result of round 0 + additive increase.

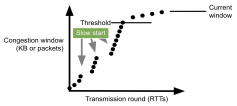


Solution – TCP CN (AIMD)



Recap – Improvements TCP Tahoe

+ threshold - fixed number N and after congestion $N = \frac{CWND}{2}$
+ slow start - up to threshold apply multiplicative increase by 2. Ex: 1, 2, 4, 8.

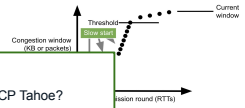


* CWND = Congestion Window

Recap – Improvements TCP Tahoe

+ threshold - fixed number N and after cong[illegible]ion $N = \frac{CWND}{2}$
+ slow start
apply multi
2. Ex: 1, 2, [illegible]

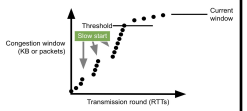
Disadvantage of TCP Tahoe?

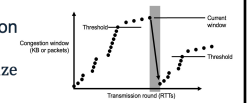


* CWND = Congestion Window

Recap – Improvements TCP Tahoe

+ threshold - fixed number N and after congestion $N = \frac{CWND}{2}$
+ slow start - up to threshold apply multiplicative increase by 2. Ex: 1, 2, 4, 8.
- no fast recovery - after congestion Tahoe sets window size = initial window size

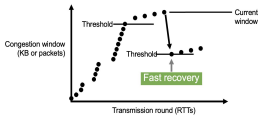




* CWND = Congestion Window

Recap – Improvements TCP Reno

+ threshold - fixed number N and after congestion $N = \frac{CWND}{2}$
+ slow start - up to threshold apply multiplicative increase by 2. Ex: 1, 2, 4, 8.
+ fast recovery - after congestion: window size = new threshold value



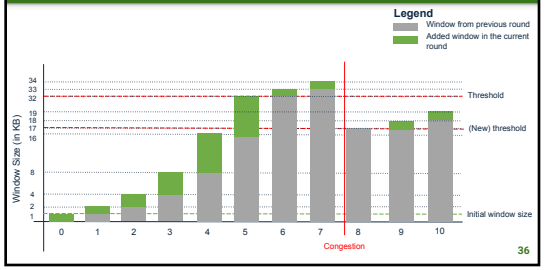
Exercise 5 – Improvements - TCP Reno

An application is sending data using **TCP Reno** (AIMD, fast recovery) with the following configurations:

1. The **initial threshold** is set at **32 KB**.
2. The **initial congestion window** size is **1 KB**.
3. Additive increase **adds 1 KB** to the window size every round.

The **congestion** is detected after **round 7**. Model the window size round by round **until round 10**. Start with round 0 and in round 1 is the result of **round 0 + multiplicative increase**.

Solution – Improvements - TCP Reno

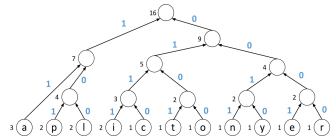


BREAK!

APPLICATION LAYER ENCODINGS

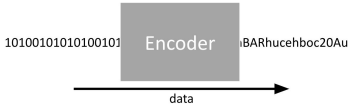
Recap – Why Application Layer Encoding?

+ support of different data types (e.g. images, videos, audio)
+ data compression

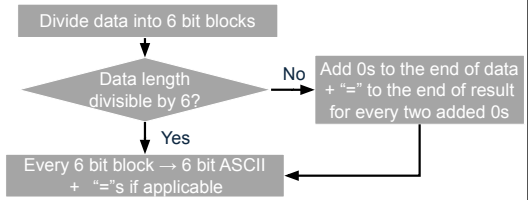


Recap – Base64 Encoding (1/2)

+ multimedia communication
+ on legacy systems designed for ASCII transmission



Recap – Base64 Encoding (2/2)



Exercise 6 – Base64 Encoding

The word **"dogs"** is written in **full ASCII** (table down below).
Encode the word **"dogs" in Base64**
- The Base64 alphabet is [A-Za-z0-9+/].
- E.g.: 000000 → A, 000001 → B, 111111→ /

a	b	c	d	e	f	g	h	i	j	k	l	m
0x61	0x62	0x63	0x64	0x65	0x66	0x67	0x68	0x69	0x6a	0x6b	0x6c	0x6d
n	o	p	q	r	s	t	u	v	w	x	y	z
0x6e	0x6f	0x70	0x71	0x72	0x73	0x74	0x75	0x76	0x77	0x78	0x79	0x7a

Solution – Base64 Encoding

Setup:
- Encode the word "dogs" in Base64
- The Base64 alphabet is [A-Za-z0-9+/].

```
d = 0x64 = 0110 0100
o = 0x6f = 0110 1111
g = 0x67 = 0110 0111
s = 0x73 = 0111 0011

01100100 01101111 01100111 01110011
011001 000110 111101 100111 011100 110000
25     6      61     39     28     48
Z      G      9      n      c      w==
```

Answer: ZG9ncw==

Recap – Huffman Encoding (1/2)

Lossless compression algorithm.

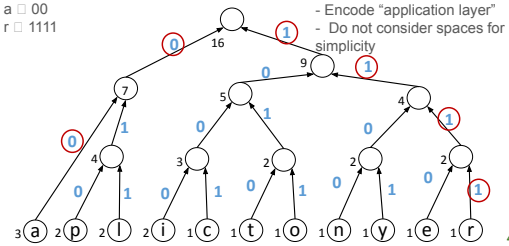
+ Used in JPEG
+ Enables real time video and audio streaming

Idea: The more frequent the symbol, the less bits you encode it with

Recap – Huffman Encoding (2/2)

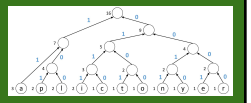
a ☐ 00
r ☐ 1111

- Encode "application layer"
- Do not consider spaces for simplicity



Overview

1. Transport Layer
   a. Sequence Numbers
   b. Fast Retransmission
   c. Congestion Control
2. Application Layer Encodings
   a. Base64 Encoding
   b. Huffman Encoding



Thanks to this amazing team!

Quiz Time!

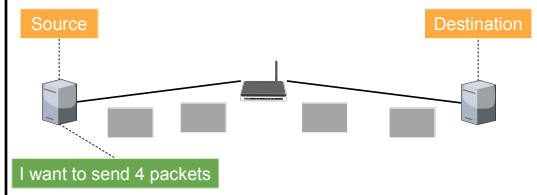
Quiz Instructions

1. Keep quiz **face down** until the quiz starts
2. Do the quiz by **yourself**: no calculators, etc.
3. No talking, phones, etc., during the quiz
4. Select answer by filling in the box
   a. ✓ Good: ■
   b. × Bad: ☒
5. Hand in your quiz at the end

✨ Good Luck on The Final!

EXTRA MATERIAL

Recap – Initial Sequence Number (ISN)



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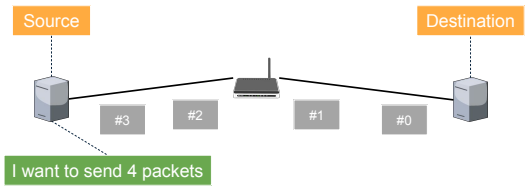

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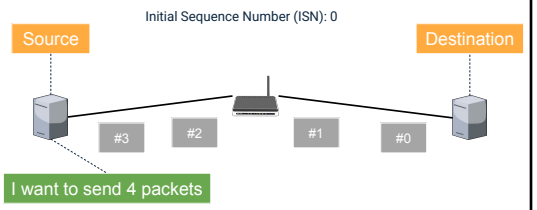
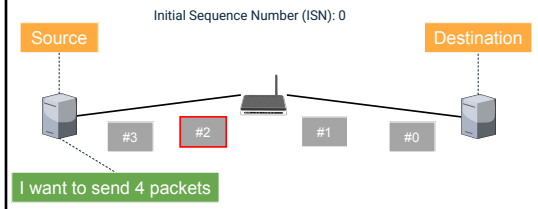


Recap – Initial Sequence Number (ISN)



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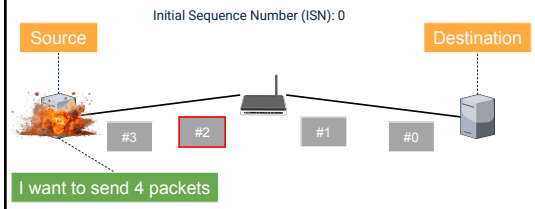

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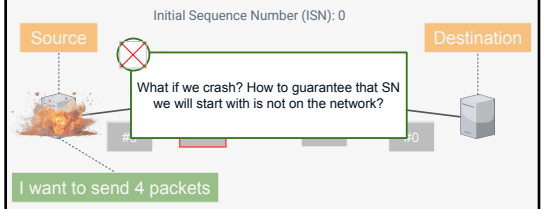
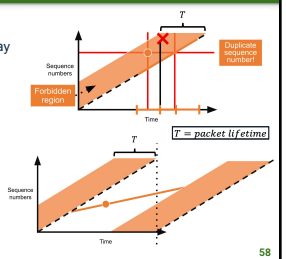


Recap – Clock-Based Initial Sequence Numbers

1. Base initial SN on some clock in a way that would guarantee **absence of duplicates.**
2. The clock is assumed to continue running even if the host goes down.
3. Forbidden region: A window of time and sequence space that must not overlap with the potential lifetime of previously sent packets.



Exercise 7 – Forbidden Regions

Consider a TCP CN protocol that uses a time-of-day clock to determine initial packet sequence numbers. The clock uses a **10-bit counter**, and ticks once every **125 milliseconds**. The maximum packet lifetime is **64 seconds**.

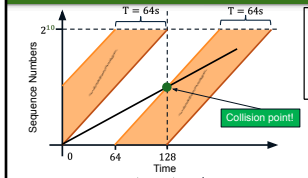
If the sender sends **4 packets per second** and the sequence number increment per packet sent, how long could the connection last without entering the forbidden region from above?

Solution (1/2) – Forbidden Regions

Setup:
- Clock counter: 10 bits
- Clock tick: every 125 ms
- Max packet lifetime: 64 seconds
- Send rate: 4 packets per second

- SN Range = 2^{10}
- Ticks per second = $\frac{1}{\text{clock tick}} = \frac{1}{0.125\text{s}} = 8$, where $0.125\text{s} = 1\text{ms} \times 1\times10^{-3}\text{s}$
- Wrap around time = $\frac{\text{SN Range}}{\text{Ticks per second}} = \frac{2^{10}}{8} = \frac{2^{10}}{2^3} = 2^7 = 128$

Solution (2/2) – Forbidden Regions



Setup:
- Clock counter: 10 bits
- Clock tick: every 125 ms
- Max packet lifetime: 64 seconds
- Send rate: 4 packets per second

- SN Range = 2^{10}
- Ticks per second = $\frac{1}{0.125} = 8$
- Wrap around time = $\frac{2^{10}}{2^3} = 128s$

- Clock: $y = 8x$ or $y = 8(x - 128)$
- Packets SN: $y = 4x$
- Forbidden Region: $y = 8(x + 64)$ or $y = 8(x - 128 + 64) = 8(x - 64)$

$4x = 8(x - 64)$
$4x = 8x - 2^9$
$-4x = -2^9$
$x = \frac{2^9}{2^2} \rightarrow 2^7 = \mathbf{128}$

Answer: 128 seconds

Legend: Initial Sequence Numbers, Forbidden Region, Sequence Number

Exercise 8 – Forbidden Regions

Consider a TCP CN protocol that uses a time-of-day clock to determine initial packet sequence numbers. The clock uses a **9-bit counter**, and ticks once every **250 milliseconds**. The maximum packet lifetime is **32 seconds**.

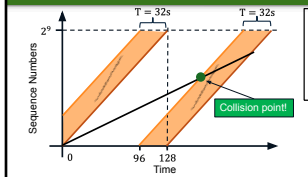
If the sender sends **3 packets per second**, how long could the connection last without entering the forbidden region from above?

Solution (1/2) – Forbidden Regions

Setup:
- Clock counter: 9 bits
- Clock tick: every 250 ms
- Max packet lifetime: 32 seconds
- Send rate: 3 packets per second

- SN Range = 2^9
- Ticks per second = $\frac{1}{\text{clock tick}} = \frac{1}{0.250s} = 4$ ($1ms = 1 \times 10^{-3}s$)
- Wrap around time = $\frac{\text{SN Range}}{\text{Ticks per second}} = \frac{2^9}{4} = \frac{2^9}{2^2} = 2^7 = 128$

Solution (2/2) – Forbidden Regions



Setup:
- Clock counter: 9 bits
- Clock tick: every 250 ms
- Max packet lifetime: 32 seconds
- Send rate: 3 packets per second

- SN Range = 2^9
- Ticks per second = $\frac{1}{0.250} = 4$
- Wrap around time = $\frac{2^9}{2^2} = 128s$

- Clock: $y = 4x$ or $y = 4(x - 128)$
- Packets SN: $y = 3x$
- Forbidden Region: $y = 4(x + 32)$ or $y = 4(x - 128 + 32) = 4(x - 96)$

$3x = 4(x - 96)$
$3x = 4x - 384$
$-x = -384$
$x = \mathbf{384\ s}$

Answer: 384 seconds

Legend: Initial Sequence Numbers, Forbidden Region, Sequence Number

Exercise 9 – Base64 Encoding

Translate the following Base64 string to 8 bit ASCII:
YmFzZQ==

a	b	c	d	e	f	g	h	i	j	k	l	m
0x61	0x62	0x63	0x64	0x65	0x66	0x67	0x68	0x69	0x6a	0x6b	0x6c	0x6d
n	o	p	q	r	s	t	u	v	w	x	y	z
0x6e	0x6f	0x70	0x71	0x72	0x73	0x74	0x75	0x76	0x77	0x78	0x79	0x7a

Solution – Base64 Encoding

```
Y = 24 = 011000      Z = 25 = 011001
m = 38 = 100110      z = 51 = 110011
F = 5  = 000101      Q = 16 = 010000
```

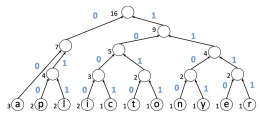
YmFzZQ==

```
011000 100110 000101 110011 011001 01
011000 100110 000101 110011 011001 010000
01100010 01100001 01110011 01100101
0x62 (b) 0x61 (a) 0x73 (s) 0x65 (e)
```

Answer: base

Exercise 10 – Huffman Encoding

- Create a Huffman coding for “a cat in a hat” (including spaces).
- What is the length difference between ASCII (8-bit per symbol) encoding and Huffman coding?



Solution – Huffman Encoding

Answer: 76

“a cat in a hat”
ASCII = 112 bits
Huffman = 36 bits

A = 0 0
_ = 0 1
T = 1 0
C = 1 1 0 0
N = 1 1 0 1
I = 1 1 1 0
H = 1 1 1 1