Note: We will start at 12:53 pm ET

18-441/741: Computer Networks
Lect yer III

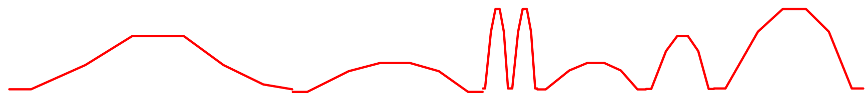
Swarun

Physical Layer: Outline

- Digital networks
- Characterization of Communication Channels
- Fundame nsmission
- Modems
- Line Coding
- Error Detection and Cor
- Wired PHY 101 (if time permits)
- Wireless PHY 101

From Signals to Packets

Analog Signal



"Digital" Signal

Bit Stream 0 0 1 0 0 0 1

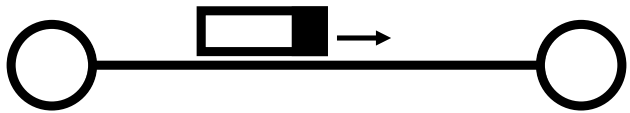
Packets

0100010101011100101010101011101110000001111010101110101010101101011010111001

Header/Body **Header/Body** **Header/Body**

Packet Transmission

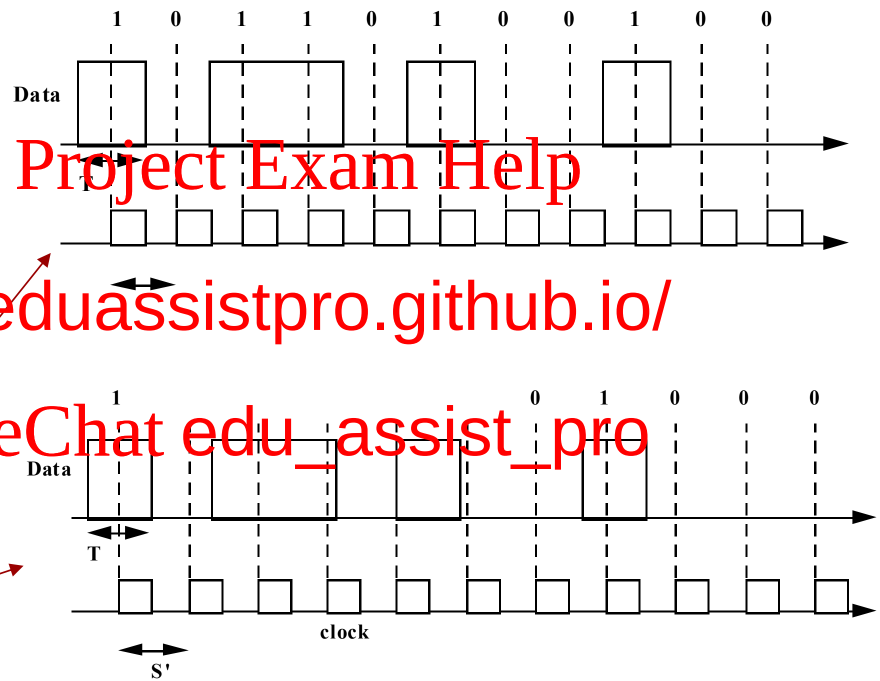
Sender



Receiver

Synchronization

- Synchronization of clocks in transmitters and receivers.
  - clock drift causes a loss of synchronization
- Example: ass
  and ‘0’ are represented by V volts and 0 volts respectively
  - Correct reception
  - Incorrect reception due to slow clock at the receiver

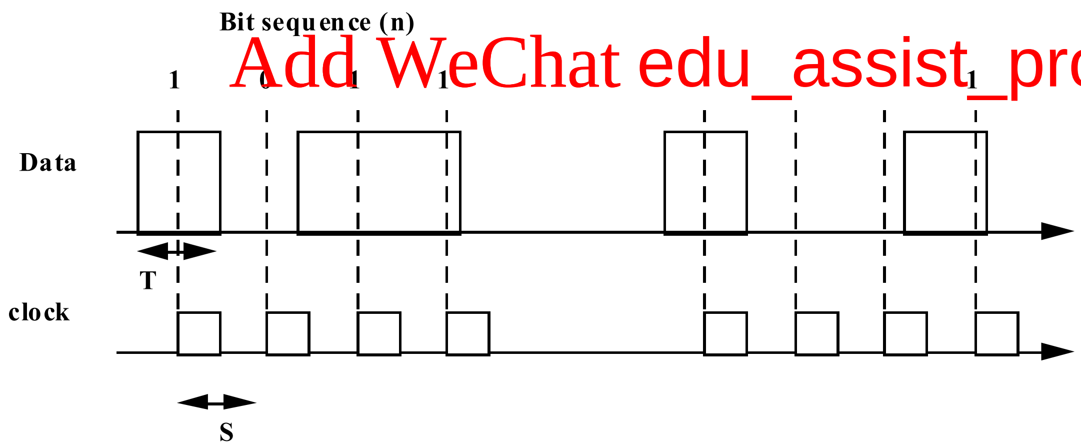


Synchronization (cont')

- How to avoid a loss of synchronization?
  - Asynchronous transmission
  - Synchro

Asynchronous Transmission

- Avoids synchronization loss by
  - specifying a short maximum length for the bit sequences (so that clock doesn't drift much within sequence)
  - and resetting the clock in the beginning of each bit sequence (by using
- Accuracy o

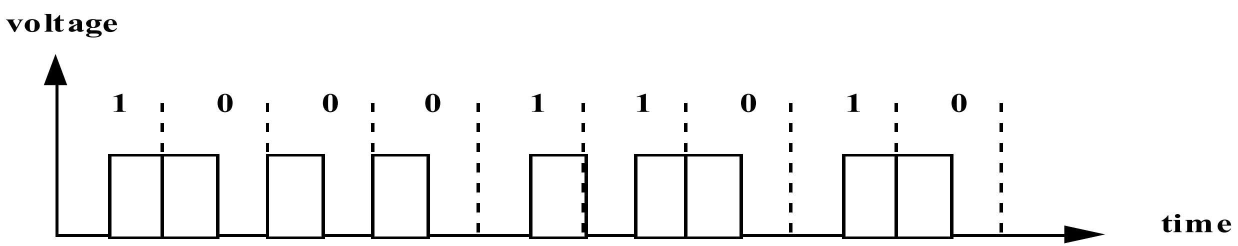


Asynchronous transmission: ASCII code

- ASCII (American National Standard Code for Information Interchange) code
  - 7 bits to ols, and control charact arriage Return)='0001101')
  - Asynchronous transmissi uences of 8 bits=one start bit + 7 ASCII bits.
  - some systems add one parity bit to make number of '1' to be even number
  - i.e. '1100111'1 or '1010110'0

Synchronous Transmission

- Overcomes the inefficiency of asynchronous transmission.
- Improves efficiency by transmitting longer sequence (variable length).
- Requires extra informati te the end of the packet.



Encoding

- Encoding converts a binary information sequence into a digital signal
  - Sender then uses the digital signal to modulate the sign can recognize
- Encoding a time or in blocks of multiple bits c bol
  - Example: a symbol with ns that 3 bits are sent in each time slot
- Transmission is synchronous, i.e., a clock is used to sample the signal.
  - Receiver's clock must be synchronized with the sender's clock

Why Do We Need Encoding?

- To meets certain electrical constraints.
  - Many of them! See next slide

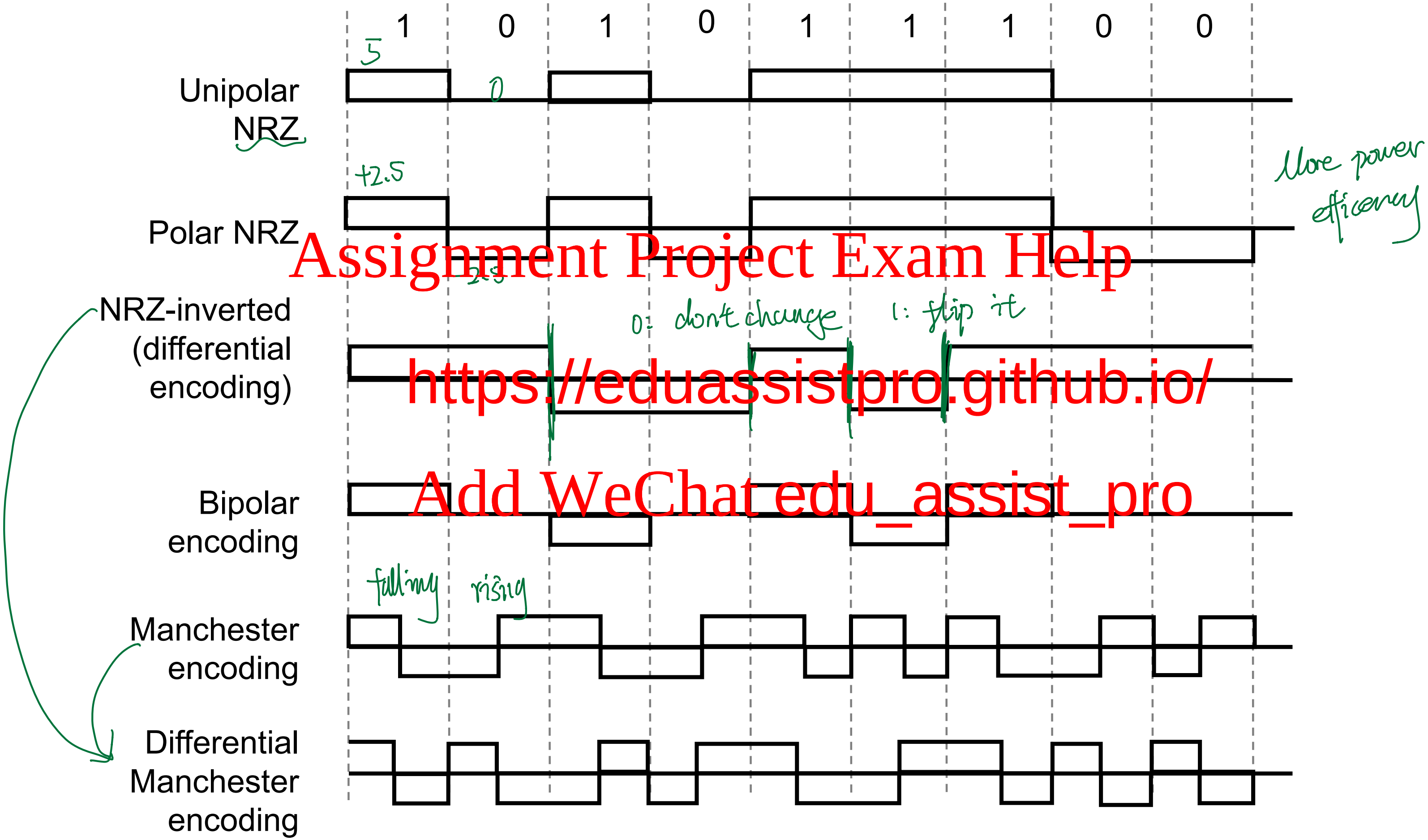
- Creates c regular data sym
  - E.g. sta ..

can not appear in data

- Can do error detection o ection

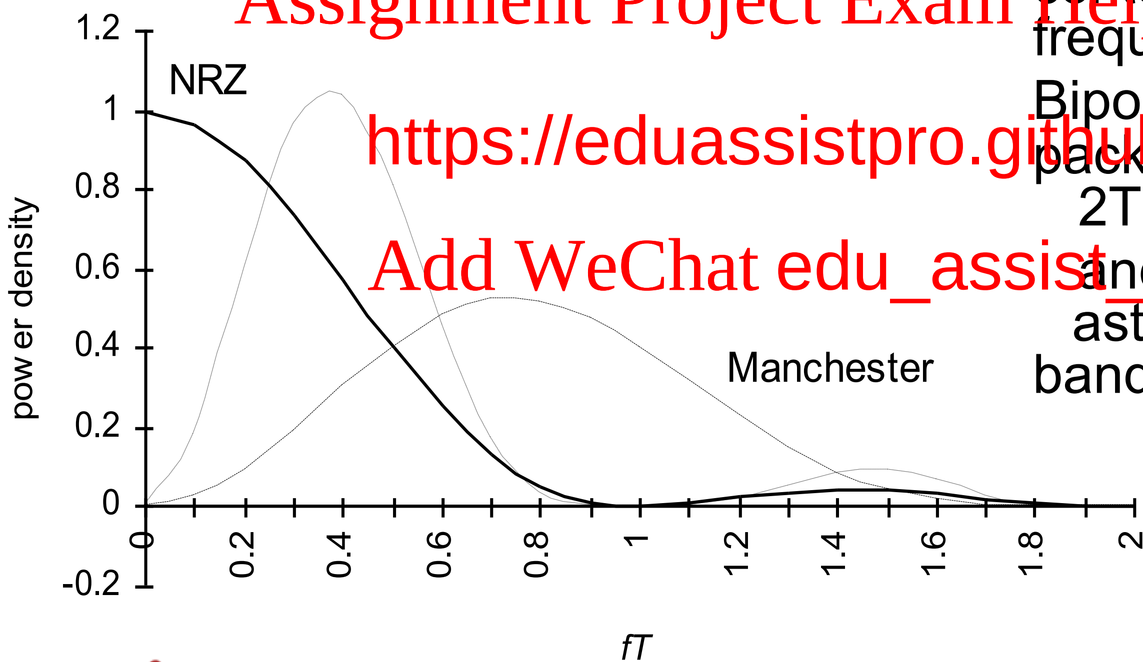
  - Some codes are illegal so receiver can detect certain classes of errors
  - Minor errors can be corrected by having multiple adjacent signals mapped to the same data symbol

Line coding examples



Spectrum of Line codes

- Assume 1’s & 0’s independent & equiprobable



- NRZ has high content at low frequencies
- Bipolar tightly packed around 2T
- anchester asteful of bandwidth

mB/nB Encoding

$n \geq m$

- m data bits are coded as *symbols* of n line bits
- Example: FDDI uses 4B5B
  - 4 data bits for 5 line bits, so 100 Mbps uses 125 MHz.
  - Uses less ding (1B2B)
- Each valid get dense transitions.
- 16 data symbols, 8 control s
  - Data symbols: 4 data bits
  - Control symbols: idle, begin frame, etc.
- Also: 8B10B (Gigabit Ethernet, Fiber channel) and 64B66B code (10G Ethernet)

4B/5B Encoding

Data	Code	Data	Code
0000	11110	1000	10010
0001	[illegible]	[illegible]	10011
0010	[illegible]	[illegible]	110
0011	10101	[illegible]	111
0100	01010	1100	11010
0101	01011	1101	11011
0110	01110	1110	11100
0111	01111	1111	11101

Quiz Question

- The following are notable absentees in 4B/5B encoding.. Why?

  - 00000 no transitions.

  - 00001
    - ➢ Need at lea

  - 11111
    - ➢ Need transit
  - 10001
    - ➢ Control symbol! (start delimiter)

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- Wired PHY 101
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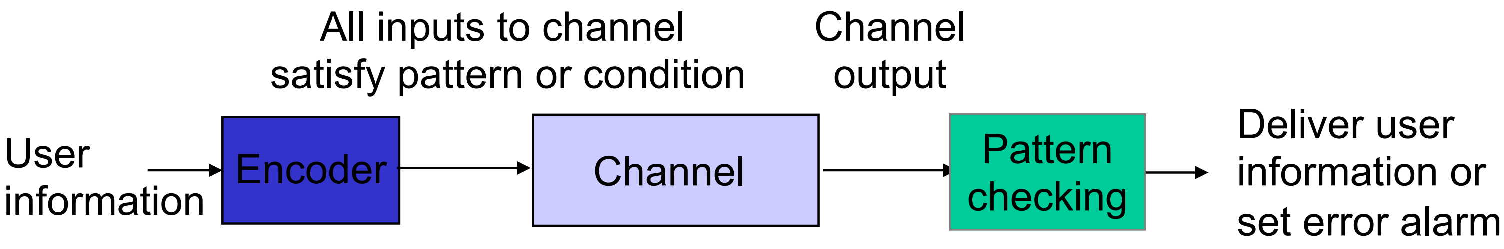
Error Control

- Channels introduce errors in digital communications
- Applications require certain reliability level
  - Data applications require error-free transfer
  - Voice & ome errors
- Error contr pplication requireme
- Error control ensures a data nsmitted to a certain level of accuracy d
- Two basic approaches:
  - Error ***detection*** & retransmission (ARQ)
  - Forward error ***correction*** (FEC)

Key Idea

- All transmitted data blocks (“codewords”) are chosen so that they satisfy a pattern
- If received block doesn’t satisfy pattern, it is in error
- Redundan possible blocks can
- Undetectable Error: Wh transforms a codeword into another v rd



Single Parity Check

- Append an parity bit to *k* information bits

Info Bits: $b_1, b_2, b_3, \ldots, b_k$

1s { even 0
odd 1

Check Bit: b = b + b + b + …+ b modulo 2

Codewor

- All codewords have even

- Receiver checks to see if # of 1s is even
  - All error patterns that create an odd # of 1 bits are detectable
  - All even-numbered error patterns are undetectable
- ASCII code is precisely such as code (7+1 bits)

Quiz Question: Single Parity Code

- Information (7 bits): (0, 1, 0, 1, 1, 0, 0)
- Parity Bit? ("True" → 1, "False" → 0)

  $b_8 = 0 + 1 + 0 + 1 + 1 + 0 = 1$

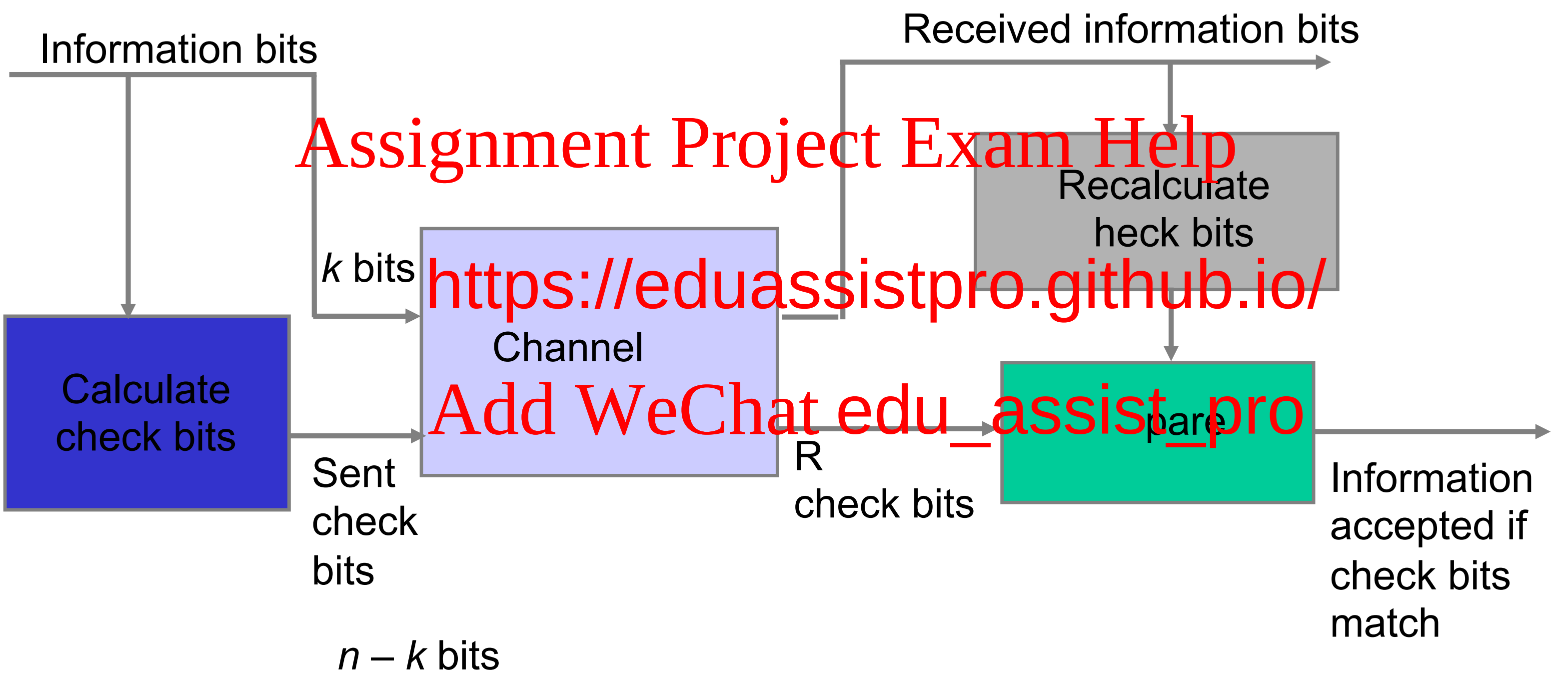
  Code 1, 0, 0, 1)

- If single error in bit 3? (0 0, 0, 1)

  – # of 1's =5, odd => Error

- If errors in bits 3 and 5? (0, 1, 1, 1, 0, 0, 0, 1)
  – # of 1's =4, even => Error not detected

Parity Checkbits & Error Detection



How good is the single parity check code?

- *Redundancy*: Single parity check code adds 1 redundant bit per k information bits: overhead = 1/(k+1)

- *Coverage*: all error patterns with odd # of errors can

  – An error le with 1's where errors occur and 0'

  – Of 2^{k+1} binary (k+1)-tuple so 50% of error patterns can be detected

- Is it possible to detect more errors if we add more check bits?
- Yes, with the right codes

What if bit errors are random?

- Many transmission channels introduce bit errors at random, independently of each other, and with probability *p*
- Some error patterns are more probable than others:

$$P[10000000] = p(1-p)^7 = (1-p)^8\left(\frac{p}{1-p}\right) \text{ and}$$

$$P[110 \ldots \left(\frac{p}{1-p}\right)^2$$

- In any worthwhile channel $p<0.5$, and s
- It follows that patterns with 1 error are more likely than patterns with 2 errors and so forth
- What is the probability that an undetectable error pattern occurs?

Single parity check code with random bit errors

- Undetectable error pattern if even # of bit errors:

$$P[\text{error detection failure}] = P[\text{undetectable error pattern}]$$

$$= P[\text{error patterns with even number of 1s}]$$

$$= \binom{n}{2} p^2 (1 \quad {}^{n-2} \quad \binom{n}{\ } \quad {}^{4} \quad {}^{n-4} \quad .$$

- Quiz! What's the probab 2, *p=10*$^{-3}$*?*

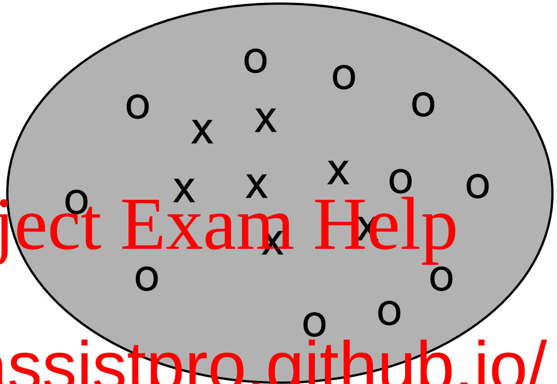
$$P[\text{undetectable error}] = \binom{32}{2}(10^{-3})^2(1-10^{-3})^{30} + \binom{\ }{4}(10^{-3})^4(1-10^{-3})^{28}$$

$$\approx 496\,(10^{-6}) + 35960(10^{-12}) \approx 4.96(10^{-4})$$

- For this example, roughly 1 in 2000 transmissions will result in an undetectable error

What is a good code?

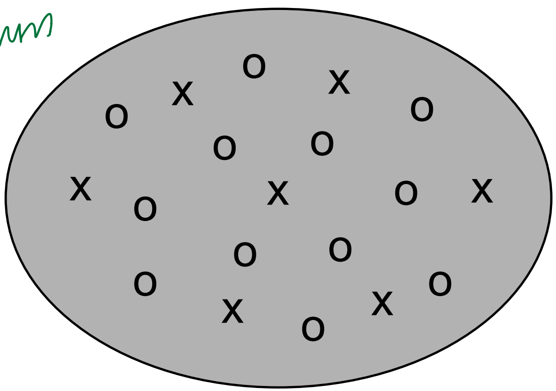
- Most channels will have relatively few bit errors
- Erroneous codewords transmitted over those channels will n-tuples
- If valid codewords are close to each other, then detection failures may occur
- Good codes should the minimum maximize separation between valid codewords



Poor distance properties

codewords

codewords



Good distance properties

Two-Dimensional Parity Check

- More parity bits to improve coverage
- Arrange information as columns
- Add single parity bit to each column
- Add a final
- Used in ea

1	0	0	1	0	0
0	1	0	0	0	1
1	0	0	1	0	0
1	1	0	1	1	0
1	0	0	1	1	1

Last column consists of check bits for each row

Bottom row consists of check bit for each column

Error-detecting capability

1	0	0	1	0	0
0	0	0	0	0	1
1	0	0	1	0	0
1	1	0	1	1	0
1	0	0	1	1	1

One error

detect + correct

1	0	0	1	0	0
0	0	0	0	0	1
1	0	0	1	0	0
1	0	0	1	1	0
1	0	0	1	1	1

Two errors

detect only

1, 2, or 3 errors can always be detected; Not all patterns >4 errors can be detected

1	0	0	1	0	0
0	0	0	1	0	1
1	0	0	1	0	0
1	0	0	1	1	0
1	0	0	1	1	1

Three errors

detect only

1	0				
0	0				
1	0	0	1	0	0
1	0	0	0	1	0
1	0	0	1	1	1

Four errors

rectangler shaped error cannot be detect

Arrows indicate failed check bits

Other Error Detection Codes

- Many applications require very low error rate
- Need codes that detect more number of errors
- Single parity check codes do not detect enough errors

- Two-dimen many check bits

- The following error detecti e widely used in practice:
  - Internet Check Sums
  - CRC Polynomial Codes

Internet Checksum

- Several Internet protocols (e.g. IP, TCP, UDP) use check bits to detect errors in the ***header***
- A checksum is calculated for header contents and included i
- Checksu d at every router, so algorithm selec of implementation in softwar
- Let header consist of L, 16-bit words,

  $\mathbf{b}_0, \mathbf{b}_1, \mathbf{b}_2, \ldots, \mathbf{b}_{L-1}$
- The algorithm appends a 16-bit checksum $\mathbf{b}_L$

Checksum Calculation

The checksum $\mathbf{b}_L$ is calculated as follows:

- Treating each 16-bit word as an integer, find

$$\mathbf{x} = \mathbf{b}_0 + \mathbf{b}_1 + \mathbf{b}_2 + \ldots + \mathbf{b}_{L-1} \text{ modulo } 2^{16}-1$$

- The checks

$$\mathbf{b}_L = -\mathbf{x}$$

Thus, the headers must sati ing ***pattern*** at the receiver:

$$\mathbf{0} = \mathbf{b}_0 + \mathbf{b}_1 + \mathbf{b}_2 + \ldots + \mathbf{b}_{L-1} + \mathbf{b}_L \text{ modulo } 2^{16}-1$$

- The checksum calculation is carried out in software using one's complement arithmetic

Internet Checksum Example

Use Modulo Arithmetic

- Assume 4-bit words
- Use mod 2^4-1 (= 15) arithmetic
- $\underline{b}_0$=1100 =
- $\underline{b}_1$=1010 = 10
- $\underline{b}_0$+$\underline{b}_1$=12+10=7 mod15
- $\underline{b}_2$ = -7 = 8 mod15
- Therefore
- $\underline{b}_2$=1000

Use Binary Arithmetic

- Note 16 =1 mod15
- So: 10000 = 0001

bit wraps

00+1010
=10110
=10000+0110
=0001+0110
=0111
=7

Take 1's complement

b_2 = -0111 =1000

Polynomial Codes

- Polynomials instead of vectors for codewords
- Polynomial arithmetic instead of check sums

- Implemented using shift-register circuits
- Also calle *ck (CRC)*

- Most data communicati ds use polynomial codes for err n

  – Have very simple hardware implementations
- Polynomial codes also basis for powerful error-correction methods

Binary Polynomial Arithmetic

- Binary vectors map to polynomials

$$(i_{k-1}, i_{k-2}, \dots, i_2, i_1, i_0) \rightarrow i_{k-1}x^{k-1} + i_{k-2}x^{k-2} + \dots + i_2x^2 + i_1x^1 + i_0$$

Addition:

$$(x^7 + x^6 + 1) +$$

$$= x^7 + (1+1$$

$$= x^7 + x^5 + \qquad 0 \bmod 2$$

Multiplication:

$$(x+1)(x^2+x+1) = x(x^2+x+1) + 1(x^2+x+1)$$

$$= (x^3+x^2+x) + (x^2+x+1)$$

$$= x^3+1$$

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Binary Polynomial Division

- Division with Decimal Numbers

```
          34        ← quotient
    35 ) 1222       ← dividend
          105
          172
          140
           32       ← remainder
divisor
```

dividend = quotient x divisor + remainder

1222 = 34 x 35 + 32

- Polynomial Division

$$
\begin{array}{rl}
 & x^3 + x^2 \qquad\qquad\qquad (x) \text{ quotient} \\
\text{divisor: } x^3 + x + 1) & x^6 + x^5 \quad \text{dividend} \\
 & x^6 + \quad\; x^4 + x^3 \\
\hline
 & x^5 + x^4 + x^3 \\
 & x^5 + \quad\; x^3 + x^2 \\
\hline
 & x^4 + \quad\; x^2 \\
 & x^4 + \quad\; x^2 + x \\
\hline
 & x \quad = r(x) \text{ remainder}
\end{array}
$$

Note: Degree of r(x) is less than degree of divisor

$$
\begin{array}{rl}
 & x^3 + x^2 + x \\
x^3 + x + 1) & x^6 + x^5 \\
 & x^6 \quad + x^4 + x^3 \\
\hline
 & x^5 + x^4 + x^3 \\
 & x^5 \quad + x^3 + x^2 \\
\hline
 & x^4 + x^2 \\
 & x^4 + x^2 + x \\
\hline
 & x
\end{array}
$$

Polynomial Coding

- k information bits define polynomial of degree k-1

$$i(x) = i_{k-1}x^{k-1} + i_{k-2}x^{k-2} + \ldots + i_2x^2 + i_1x + i_0$$

- Code has binary generating polynomial of degree n-k

$$g(x) = x^{n-k} + \ldots x^{n-k-1} + \ldots x^2 + g_1x + 1$$

- Find *remaind*... egree n-k-1

$$g(x)\,\overline{)\,x^{n-k}\,i(x)}^{\;q(x)}$$

$r(x)$

... x) + r(x)

- Define the *codeword polynomial* of degree n-1

$$\boxed{\underbrace{b(x)}_{\text{n bits}} = \underbrace{x^{n-k}i(x)}_{\text{k bits}} + \underbrace{r(x)}_{\text{n-k bits}}}$$

is always a multiple of g(x)

Quiz Q: Find codeword if k=4, n-k=3

And: Generator polynomial: $g(x) = x^3 + x + 1$

Information: (1,1,0,0) $i(x) = x^3 + x^2$

Encoding: $x^3 i(x) = x^6 + x^5$

Quiz Q: Find codeword if k=4, n-k=3

And: Generator polynomial: $g(x)= x^3 + x + 1$

Information: (1,1,0,0) $i(x) = x^3 + x^2$

Encoding: $x^3 i(x) = x^6 + x^5$

$$
\begin{array}{rl}
 & x^3 + x^2 + x \\
\hline
x^3 + x + 1 \,) & x^6 + x^5 \\
 & x^6 + x^4 \quad\; + x \\
\hline
 & x^5 + x^4 + x^3 \\
 & x^5 + \quad\; x^3 + x^2 \\
\hline
 & x^4 + \quad\; x^2 \\
 & x^4 + \quad\; x^2 + x \\
\hline
 & x
\end{array}
$$

Quiz Q: Find codeword if k=4, n-k=3

And: Generator polynomial: $g(x)= x^3 + x + 1$ 1 0 0 1

Information: (1,1,0,0) $i(x) = x^3 + x^2$

Encoding: $x^3 i(x) = x^6 + x^5$

$$
\begin{array}{r l}
 & x^3 + x^2 + x \\
\hline
x^3 + x + 1\ ) & x^6 + x^5 \\
 & x^6 + \qquad\quad x \\
\hline
 & x^5 + x^4 + x^3 \\
 & x^5 + \qquad x^3 + x^2 \\
\hline
 & x^4 + \qquad x^2 \\
 & x^4 + \qquad x^2 + x \\
\hline
 & x
\end{array}
$$

$$
\begin{array}{r}
1110 \\
\hline
1100000 \\
1011 \\
\hline
1110 \\
1011 \\
\hline
1010 \\
1011 \\
\hline
010
\end{array}
$$

Transmitted codeword:

$b(x) = x^6 + x^5 + x$

$\underline{b} = (1,1,0,0,0,1,0)$

The *Pattern* in Polynomial Coding

- All codewords satisfy the following **pattern**:

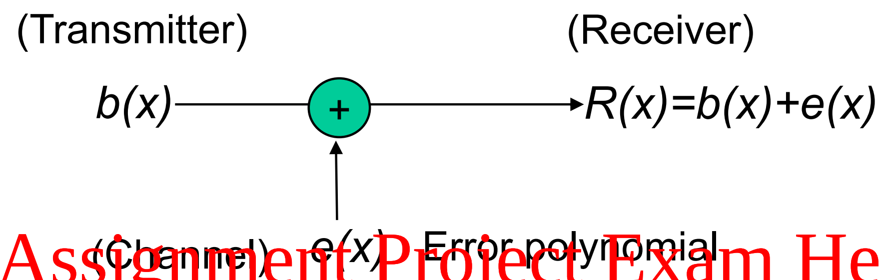
$b(x) = x^{n-k}i(x) + r(x) = q(x)g(x) + r(x) + r(x) = q(x)g(x)$

- All codewor

- Receiver should divide rec le by g(x) and check if remainder is

- If remainder is non-zero, then received n-tuple is not a codeword

Undetectable error patterns



- $e(x)$ has 1's i here
- Receiver divi $R(x)$ by $g(x)$
- Undetectable error: If $e(x)$ is a (x), that is, $e(x)$ is a non-zero codeword, t

$$R(x) = b(x) + e(x) = q(x)g(x) + q'(x)g(x)$$

- *The set of undetectable error polynomials is the set of nonzero code polynomials*
- *Choose the generator polynomial so that selected error patterns can be detected.*

Designing good polynomial codes

- Select generator polynomial so that likely error patterns are not multiples of *g(x)*
- *Detecting Single Errors*

  - $e(x) = x^i$ for error in location $i+1$
  - If *g(x)* has ... x^i

- *Detecting D*
  - $e(x) = x^i + x^j = x^i(x^{j-i}+1)$ where $j>i$

  - If *g(x)* has more than 1 term, it c
  - If g(x) is a *primitive* polynomial, it cannot divide x^m+1 for all $m<2^{n-k}-1$ (Need to keep codeword length less than $2^{n-k}-1$)
  - Primitive polynomials can be found by consulting coding theory books

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Standard Generator Polynomials

CRC = cyclic redundancy check

- CRC-8: $= x^8 + x^2 + x + 1$ ATM

- CRC-16:

- CCITT-16: $= x^{16} + x^{12} + x^5 + 1$ HDLC, XMODEM, V.41

IEEE 802, DoD, V.42

- CCITT-32:

$$= x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1$$

Hamming Codes

- Class of *error-correcting* codes
- Capable of *or* patterns
- Provably o
- Very less redundancy, e.g. r proof – adds O(log n) bits of redundanc equences

m=3 Hamming Code

- Information bits are b_1, b_2, b_3, b_4
- Equations for parity checks b_5, b_6, b_7

$$b_7 = \quad + b_2 + b_3$$

- There are 2^4=16 codewords
- (0,0,0,0,0,0,0) is a codeword

My ”simple” proof of optimality

Assume you got the following 7 bit seque and make the followi checks:

$$b_5 = b_1 \qquad\quad + b_3 + b_4$$
$$b_6 = b_1 + b_2 \qquad\quad + b_4$$
$$b_7 = \qquad + b_2 + b_3 + b_4$$

Case	b_5 match	b_6 match	b_7 match
[illegible]			
1			
b_2 flipped			
b_3 flipped			
b_4 flipped			
b_5 flipped			
b_6 flipped			
b_7 flipped			

My ”simple” proof of optimality

Assume you got the following 7 bit seque and make the followi checks:

$$b_5 = b_1 \qquad + b_3 + b_4$$
$$b_6 = b_1 + b_2 \qquad + b_4$$
$$b_7 = \qquad + b_2 + b_3 + b_4$$

Case	b_5 match	b_6 match	b_7 match
		✓	✓
1		X	✓
b_2 flipped		X	X
b_3 flipped			X
b_4 flipped	X	X	X
b_5 flipped	X	✓	✓
b_6 flipped	✓	X	✓
b_7 flipped	✓	✓	X

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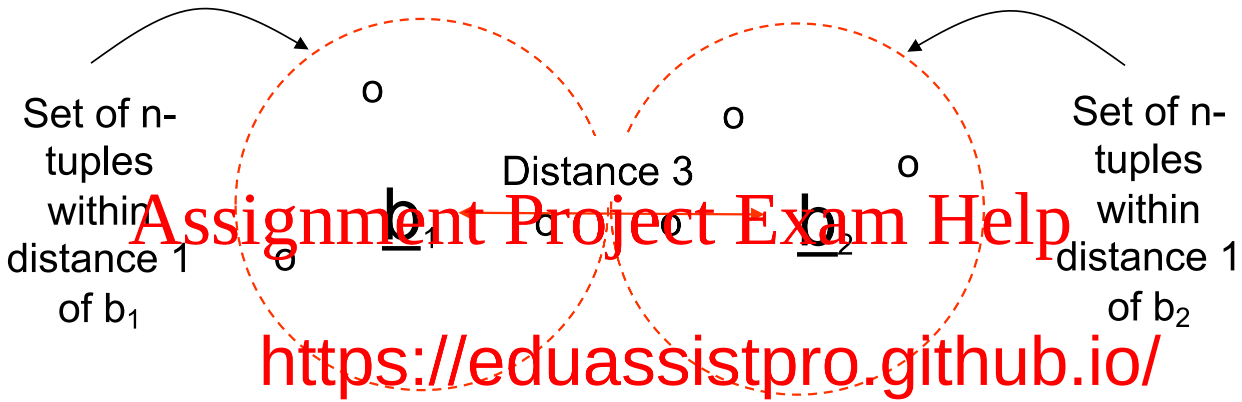
Why is Hamming a "good code"?



- Two valid bit sequences have a minim bit flips
- Spheres of distance 1 around each codeword do not overlap
- If a single error occurs, the resulting n-tuple will be in a unique sphere around the original codeword
- Thus, receiver can correct erroneous reception back to original codeword

Physical Layer: Outline

- Digital networks
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- Fundame nsmission
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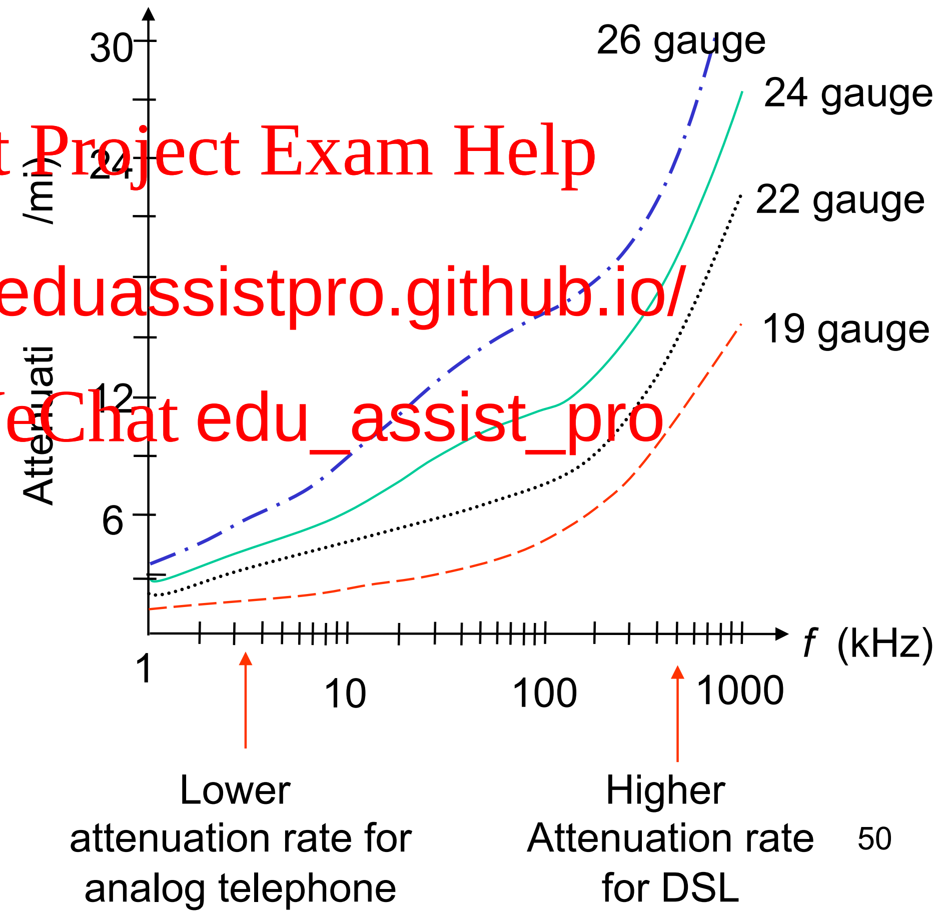
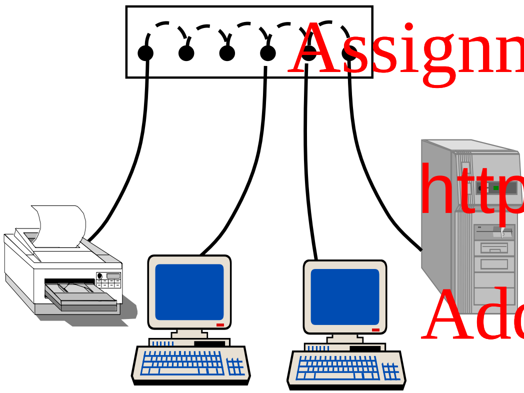
- Modems and Digital Mo
- Error Detection and Cor
- Wired PHY 101
- Wireless PHY 101

Twisted Pair

- Two insulated copper wires arranged in a regular spiral pattern to minimize interference
- Various thicknesses, e.g. 0.016 inch (24 ga
- Low cost
- Telephone subscriber loop from customer to CO
- Old trunk plant connecting telephone COs
- Intra-building telephone from wiring closet to desktop



Ethernet LANs



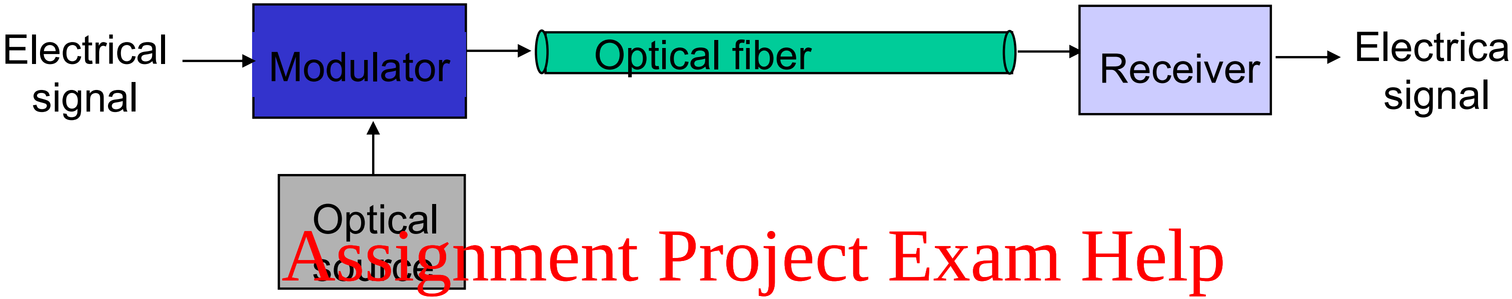
- Evolved from 10 -> 100 → 1000 Mbps to now 10Gbps
- All use twisted pair in some form!

- net
  – and, Twisted pair

  – Tw
  – Ma 100 meters

- 100B Ethernet
  – 100 Mbps, Baseband, Twisted pair
  – Four Cat3 pairs
  – Three pairs for one direction at-a-time
  – 100/3 Mbps per pair;
  – 3B6T line code, 100 meters
- 1000BASE-T
  – 8b10b encoding, Four pairs

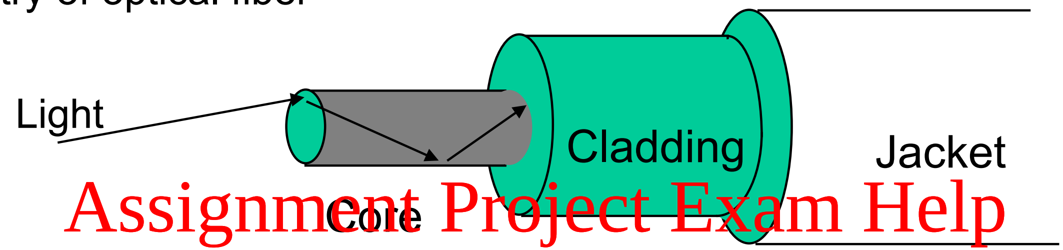
Optical Fiber



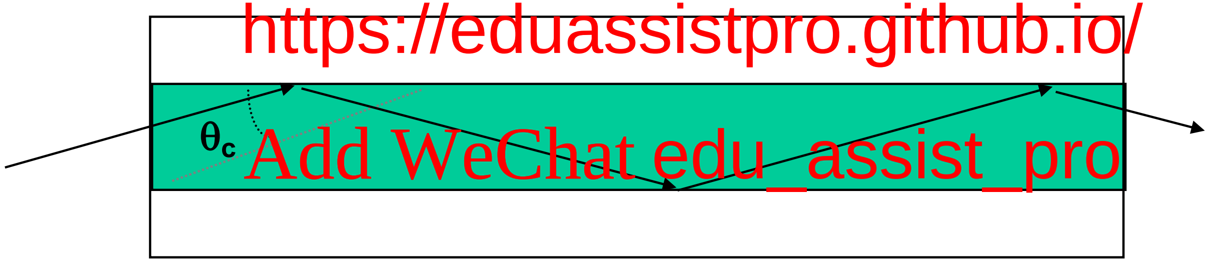
- Light source ulses of light that are transmit
  - Very long distances (>1000 km)
  - Very high speeds (>40 Gbps/wa
  - Nearly error-free (BER of 10^{-15})
- Profound influence on network architecture
  - Dominates long distance transmission
  - Distance less of a cost factor in communications
  - Plentiful bandwidth for new services

Transmission in Optical Fiber

Geometry of optical fiber



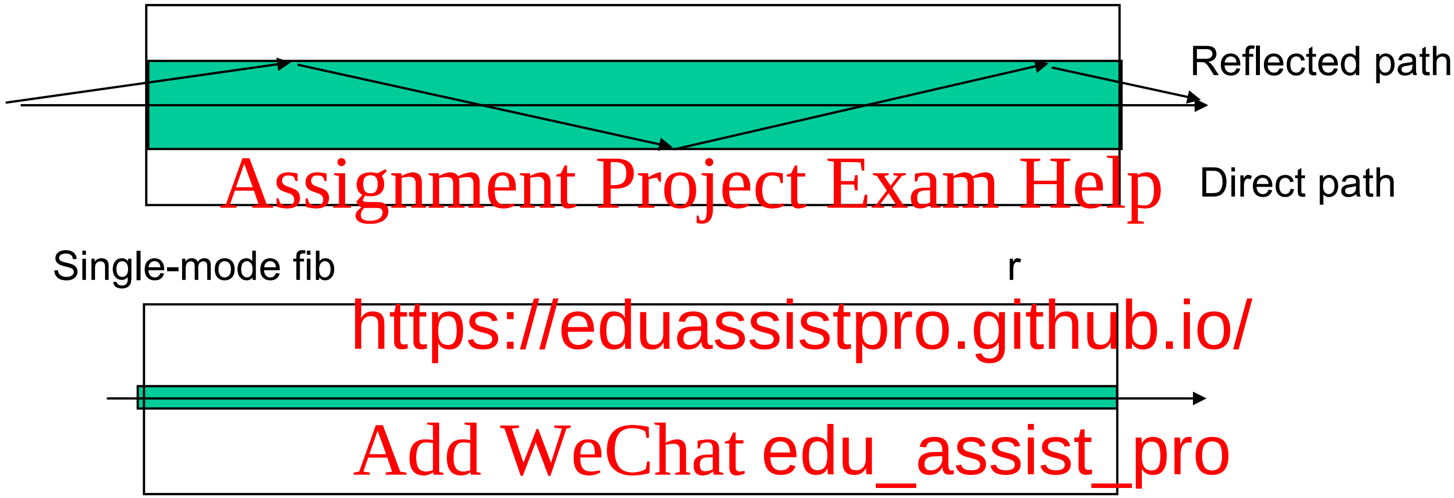
Total Internal Reflect



- Very fine glass cylindrical core surrounded by concentric layer of glass (cladding)
- Core has higher index of refraction than cladding
- Light rays incident at less than critical angle θ_c is completely reflected back into the core

Multimode & Single-mode Fiber

Multimode fiber: multiple rays follow different paths



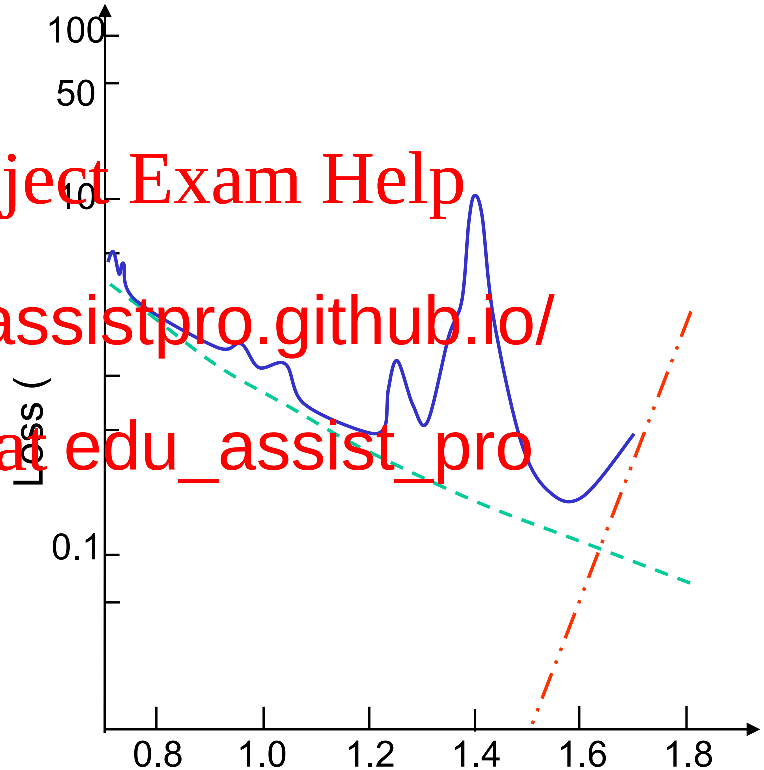
- Multi Mode: Thicker core, shorter reach
  - Rays on different paths interfere causing dispersion & limiting bit rate
- Single Mode: Very thin core supports only one mode (path)
  - More expensive lasers, but achieves very high speeds

Huge Available Bandwidth

- Optical range from λ_1 to $\lambda_1+\Delta\lambda$ contains bandwidth

$$B = f_1 - f_2 = \frac{\nu}{\quad} - \frac{\nu}{\qquad}$$

$$= \frac{\nu}{\lambda_1}\left\{\frac{\Delta\lambda / \lambda_1}{1+\Delta\lambda / \lambda_1}\right\} \cong \frac{\quad}{\lambda_1^2}$$



Quiz Question

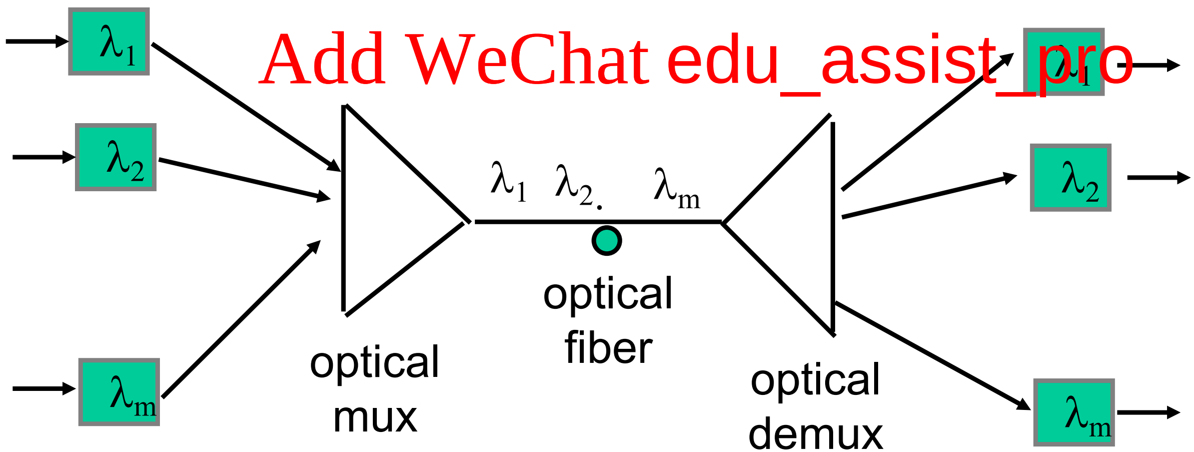
How much optical fiber bandwidth is available between:

λ_1 0 nm:

Answer: $B = \frac{2(10^8)\text{m/s}\,200\text{n}}{(1450\,\text{nm})^2}$

Wavelength-Division Multiplexing

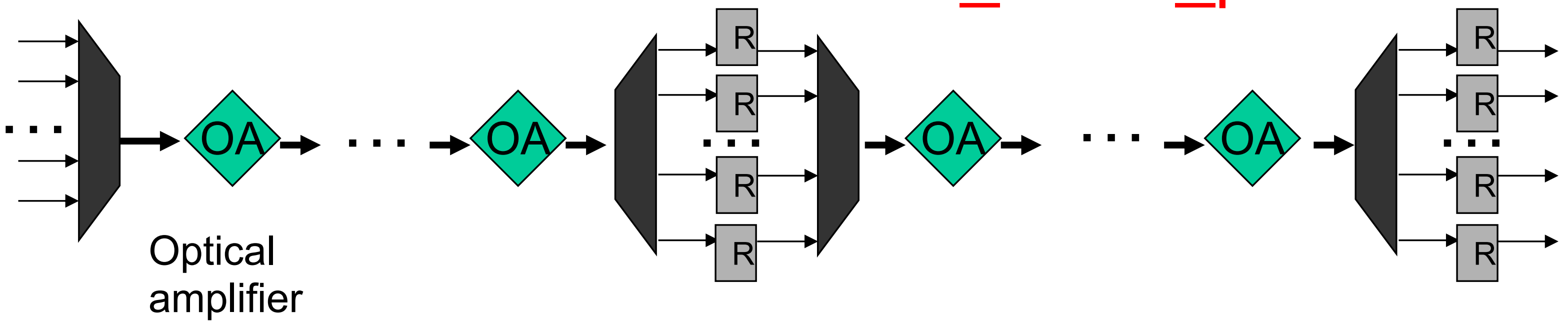
- Different wavelengths carry separate signals
- Multiplex into shared optical fiber
- Each wavelength like a separate circuit
- A single fib hs, 10 Gbps per wavele



How Do We Extend Range

- Use combinations of optical amplifiers and regenerators

- More amplifiers than regenerators (why?)



Physical Layer: Outline

- Digital networks
- Characterization of Communication Channels
- Fundame nsmission
- Line Codi
- Modems and Digital Mo
- Error Detection and Cor
- Wired PHY 101
- Wireless PHY 101