Last Lecture: Network Layer

1. *Design goals and issues*
2. *Basic Routing Algorithms & Protocols*
3. *Addressing, Fragmentation and reassembly*
4. *Internet Routing Protocols and Inter-networking*
5. *Router design*
   1. *Short History + Architectures*
   2. *Switching fabrics*
   3. *Address lookup problem* ✔
6. ~~*Congestion Control, Quality of Service*~~
7. ~~*More on the Internet's Network Layer*~~

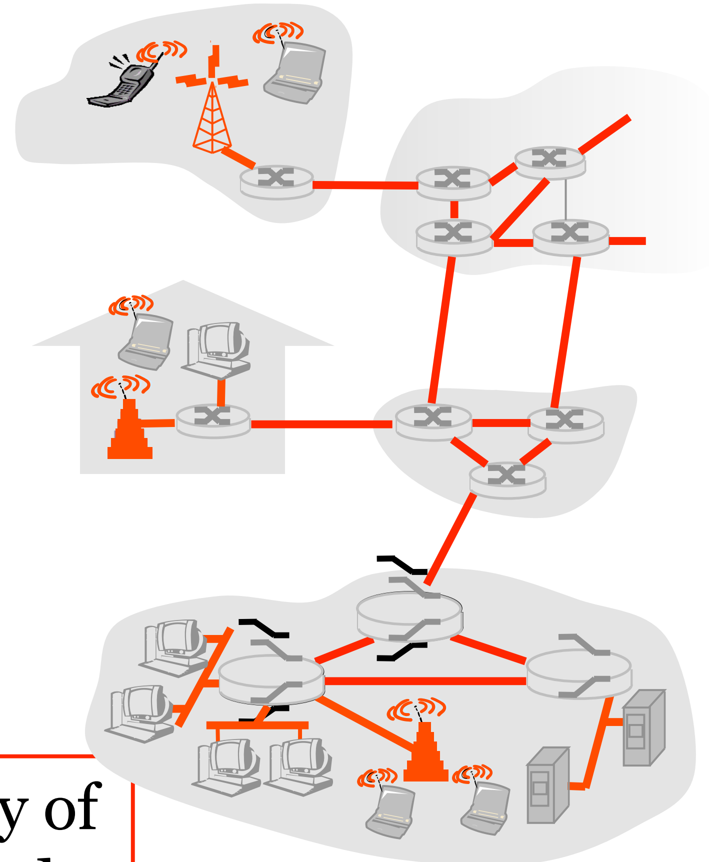
This Lecture: Data Link Layer

1. *Design goals and issues* ✔
2. *(More on) Error Control and Detection* ✔
3. *Multiple Access Control (MAC)*
4. *Ethernet, LAN Addresses and ARP*
5. *Hubs, Bridges, Switches*
6. *Wireless LANs*

What Does Link Layer Do?

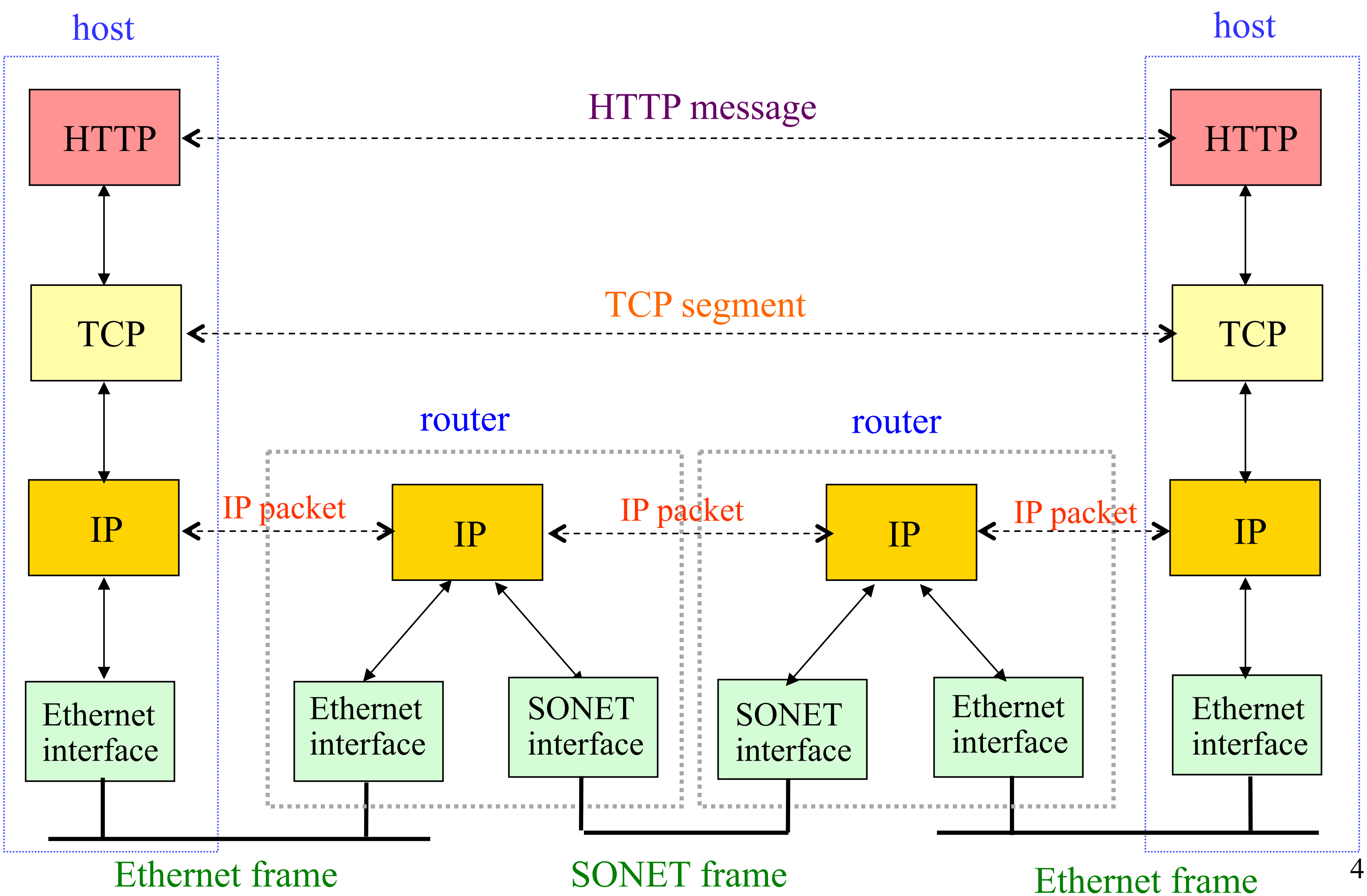
<u>Some terminology:</u>

- Hosts and routers are ***nodes***
- Communication channels that connect adjacent nodes along communication path are ***links***
  - Wired links
  - Wireless links
  - LANs
- Layer-2 packet is a ***frame***, encapsulates datagram



data-link layer has responsibility of transferring datagram from one node to adjacent node over a link

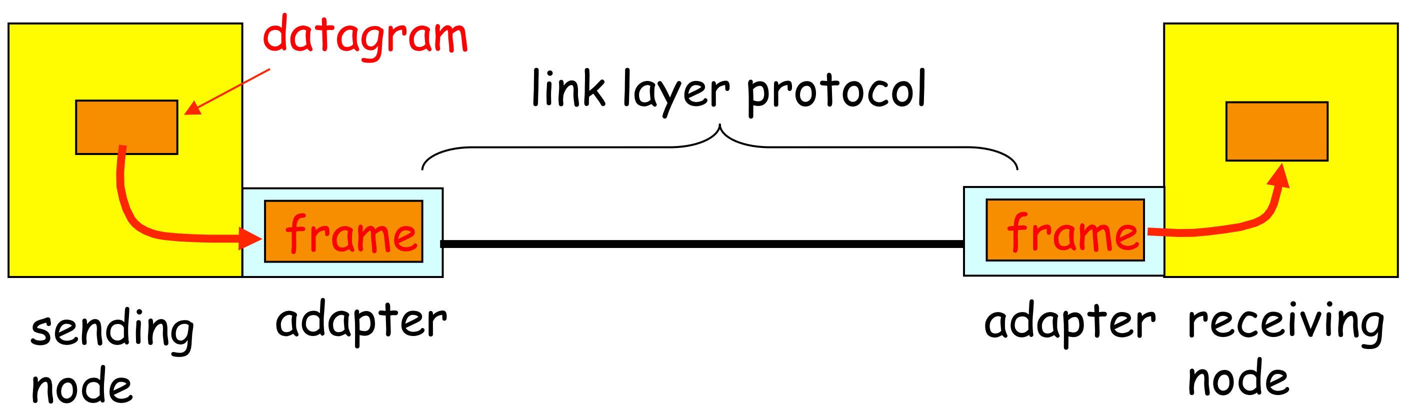
Message, Segment, Packet, Frame



Link Layer for Each Hop

- *IP packet transferred over multiple hops*
  - Each hop has a link layer protocol
  - May be different on different hops
- *Analogy: trip from Buffalo to New York*
  - Limo: Buffalo to BNI Airport
  - Plane: BNI to JFK
  - Train: JFK to Hotel
- *Refining the analogy*
  - Tourist == packet
  - Transport segment == communication link
  - Transportation mode == link-layer protocol
  - Travel agent == routing algorithm

Where Does Link Layer "Happen"?



- *Link layer implemented in adaptor (net. interface card)*
  - Ethernet card, PCMCIA card, 802.11 card
- *Sending side:*
  - Encapsulates datagram in a frame
  - Adds error checking bits, flow control, etc.
- *Receiving side:*
  - Looks for errors, flow control, etc.
  - Extracts datagram and passes to receiving node

Link Layer Services

Basic services:

- Framing and encoding
- Error detection, correction

Access services:

- Sharing a broadcast channel: multiple access
- Link layer addressing

Performance services:

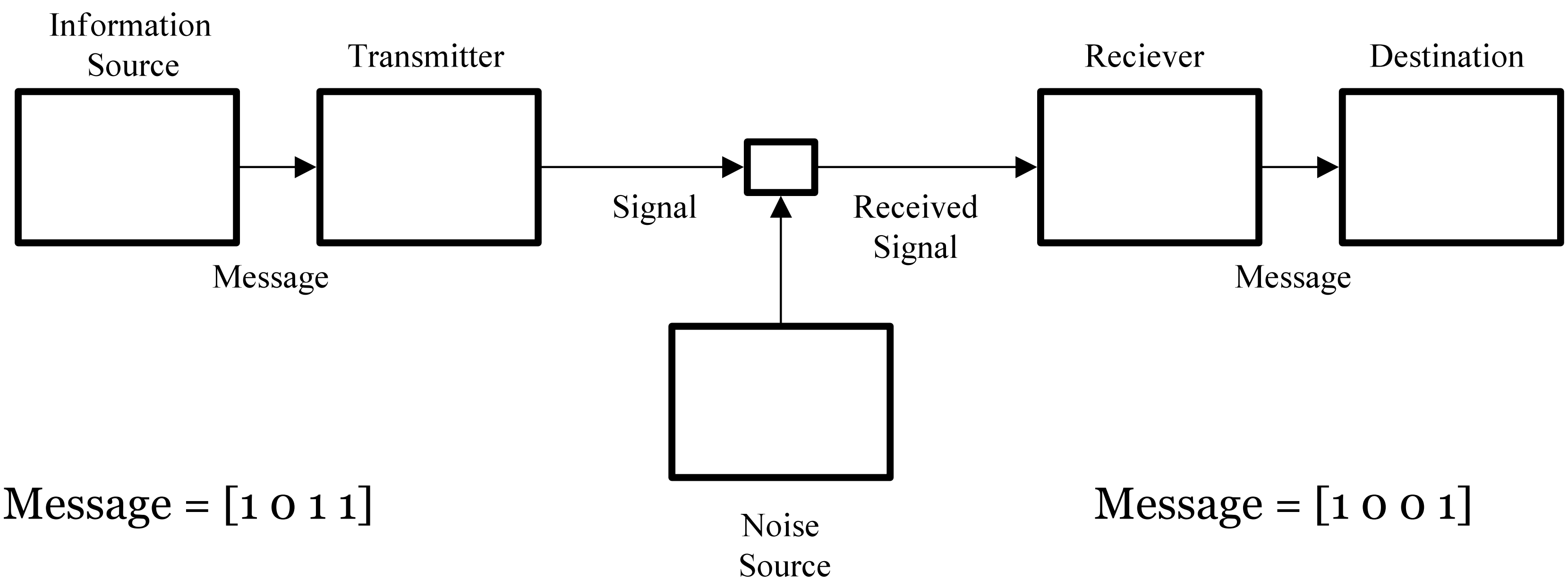
- Reliable data transfer, flow control: *done!*

Link Layer Basic Services

- *Encoding*
  - Representing the 0s and 1s
- *Framing*
  - Encapsulating packet into frame, adding header, trailer
  - Using MAC addresses, rather than IP addresses

- *Error detection*
  - Errors caused by signal attenuation, noise.
  - Receiver detecting presence of errors
- *Error correction*
  - Receiver correcting errors without retransmission

Principles of Error Detecting/Correcting Codes



Message = [1 0 1 1]

Message = [1 0 0 1]

Noise "flips" the 3rd bit

The Problem

Noisy Channel and Error Correction

Aoccdrnig to rscheearch at an Elingsh uinervtisy, it deosn't mttaer in waht oredr the ltteers in a wrod are, the olny iprmoetnt tihng is that the frist and lsat ltteer are at the rghit pclae. The rset can be a toatl mses and you can sitll raed it wouthit a porbelm. Tihs is bcuseae we do not raed ervey lteter by it slef but the wrod as a wlohe.

Principles of Error Detecting/Correcting Codes

- *Messages*: vectors of length m, i.e. $\{0,1\}^m$
- *Encoding function*: $f:\{0,1\}^m \rightarrow \{0,1\}^n$
  ($n > m$ to add redundancy)

- Given message x, send $y = f(x)$
- Receiver receive y' (possibly different from y)

- *Decoding*: get back x from y'

The Solution

Efficiency of the System

- How much extra redundancy added?
  - *n/m* is the *code rate*, want to keep near *1*
- How many errors can the system detect, correct?
  - Say, it can detect *e* bit-errors, want it to be large
- Natural tradeoff between rate and error detection capability
  - Small *n/m* implies small *e*

What Shannon + Hamming Taught Us

$$C = \{f(x) \mid x \in \{0,1\}^m\}$$

Is called the set of *codewords*

The *minimum distance* of *C* is

$$\Delta(C) = \min_{c_1 \neq c_2 \in C} (\text{Hamming-Distance}(c_1, c_2))$$

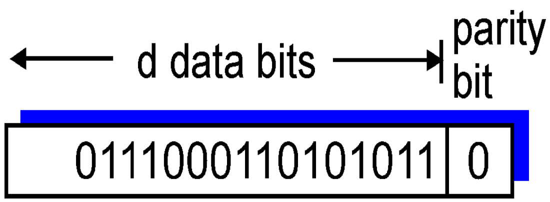
We can always detect $\Delta(C) - 1$ errors

We can always correct $\left\lfloor \frac{\Delta(C) - 1}{2} \right\rfloor$ errors

Examples We've Seen: Parity Checking

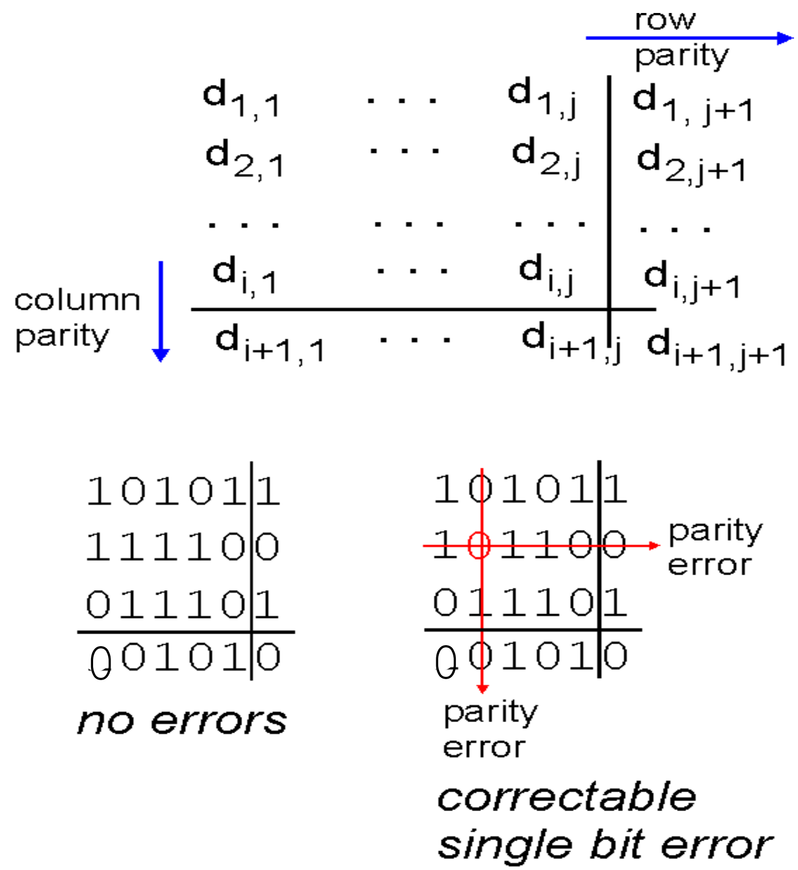
Single Bit Parity:

Detect single bit errors



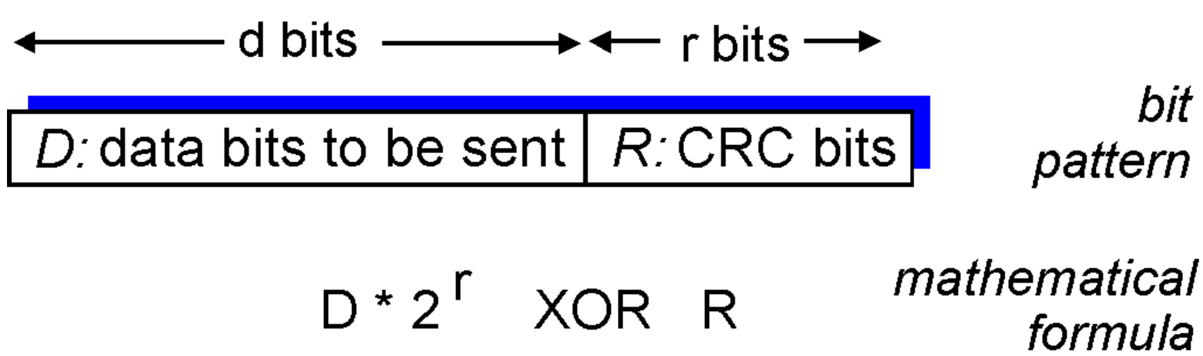
Two Dimensional Bit Parity:

Detect 3 bit-errors and correct single bit errors



CRC Code: More Sophisticated Error Detection

- View data bits, D, as a binary number
- Choose r+1 bit pattern (generator), G
- Goal: choose r CRC bits, R, such that
  - [D,R] exactly divisible by G (modulo 2)
  - Receiver knows G, divides [D,R] by G. If non-zero remainder: error detected!
- *Widely used in practice* (Ethernet, 802.11 WiFi, ATM)



CRC Example

Want:

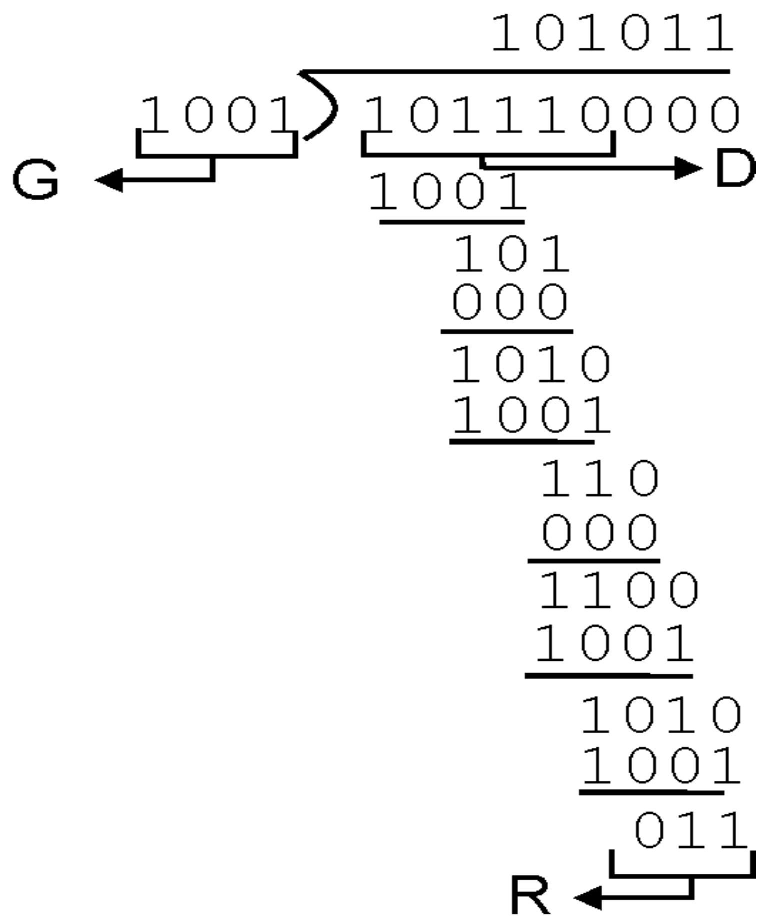
$D \cdot 2^r$ XOR R = nG

equivalently:

$D \cdot 2^r$ = nG XOR R

equivalently:

if we divide $D \cdot 2^r$ by G, want remainder R



$$R = \text{remainder}\left[\frac{D \cdot 2^r}{G}\right]$$

CRC in terms of Polynomials

- Message *M* length *k* (110011)
  - $M(x) = x^5+x^4+x+1$
- *G* is given as a *Generator Polynomial* of degree *r*
  - $CRC\text{-}12 = x^{12}+x^{11}+x^3+x^2+x^1$
  - *CRC-16, CRC-CCITT, CRC-32*
- Arithmetic Modulo 2 is now done in terms of these polynomials
  - $M(x)\,x^r = G(x)Q(x) + R(x)$
  - *R(x)* represent the bits to be added to message
- *In practice*: use circuit consisting of XOR-gates and shift registers → very fast

CRC Can Detect

- All single-bit errors
- All double-bit errors, as long as G has at least 3 1's
- Any odd number of errors, as long as G contains a factor $(x+1)$ (*why?*)
- Any burst error of length n or less
- Most larger burst errors
- Probability of undetected $(n+1)$-burst error is $1/2^{n-1}$
- Probability of undetected longer burst error is $1/2^n$