Communications Channels
CS 118
Computer Network Fundamentals
Peter Reiher

Review: Comm. as shared state

- Communication is less than most think
  - Just syntax – not semantics or intent
- Information is based on states
  - Which is based on entropy (disorder)
- We can model how state evolves
  - Each side models the other
  - Successive steps in models are how we go from sharing state to transferring files
- Noise decreases the information we can pass
  - Encodings can correct errors
  - But cannot break the Shannon limit

Communication: Roadmap

- The imperfect channel
- Making the channel real
- Automating the channel

What is “encoding a block”?

- Forward error correction
  - A way to detect and correct errors without asking for more information
- Examples:
  - Parity
  - Majority
  - Hamming
  - Reed-Solomon

Parity

- Sender
  - Add one bit to ensure a block has an EVEN (or ODD) number of 1's
  - 01011 -> 010111
- Receiver
  - Check to see if the pattern has the correct number of 1's
  - 010111 is OK
  - 011111 is BAD

What can parity help with?

- Error detection
  - Detects any ODD number of bit errors in the block
- Cost:
  - One extra bit per block
- Limits:
  - Won't detect any EVEN number of errors (regardless of parity type)
  - Cannot correct the errors

Majority

- Sender uses a repetition code
  - E.g., send each bit three times
  - 01011 -> 000111000111111
- Receiver uses majority voting
  - For each triplet, pick the majority value
  - 011111011110111 becomes 01111

What can majority help with

- Error detection
  - Detected when a group is not all the same
  - Can locate errors to each group they occur
- Error correction
  - YES, for $k < \frac{N}{2}$ errors per group
- Cost:
  - N times longer
- Limits:
  - Very high cost

Hamming

- Combines parity with sets
- Sender
  - Use the algorithm to generate parity codes within various subsets of the bits
- Receiver
  - Use the algorithm to check parity codes within various subsets. When a parity check fails, it indicates the bit position of the error

A Hamming Code Example

- Let’s say we have a 15 bit data item

d1 d2 d3 d4 d5 d6 d7 d8 d9 d10 d11 d12 d13 d14 d15

- We want to send it on a noisy channel and be able to correct a 1-bit error
- Add 5 parity bits
  - Why 5? We’ll see in a minute
- But don’t use them as a single 5-bit number
- Have each parity bit cover a subset of the overall bits

Building the Hamming Code

- We're going to send 15 bits encoded as 20 bits
  - Adding 5 parity bits to the 15 data bits
- Where do we put the 5 parity bits?
- Not at the end
- Scattered through the 20 bit encoded value
- OK, so which bits are parity bits?
- Any bit whose binary value for position contains only one 1
  - Bit 1 (1), bit 2 (10), bit 4 (100), bit 8 (1000), bit 16 (10000)

Adding the parity bits

d1 d2 d3 d4 d5 d6 d7 d8 d9 d10 d11 d12 d13 d14 d15

p1 p2 p4 p8 p16

	1	*10*	*11*	*100*	*101*	*110*	*111*	*1000*	*1001*	*1010*	*1011*	*1100*	*1101*	*1110*	*1111*	*10000*	*10001*	*10010*	*10011*	*10100*
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
p1	x		x		x		x		x		x		x		x		x		x	
p2		x	x			x	x			x	x			x	x			x	x	
p4				x	x	x	x					x	x	x	x					x
p8								x	x	x	x	x	x	x	x					
p16																x	x	x	x	x

What does each parity bit cover?

What do we mean by "cover"?

- The parity bit is calculated in the usual way
- But considering only the bits it covers
- So each of the five parity bits is computed differently
  - Considering a different (but overlapping) set of data bits

What does this buy us?

- If one bit is flipped, some parity bits will come out wrong, when checked
- Which indicates that we had an error
- But we get more than that from a Hamming code
- Let's consider an example

Hamming code example

- Data value:

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

- Add the parity bits

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

- That’s what you send
- Receiver checks using the same rules
- If all parity bits match, no single bit errors

What if there's an error?

- What if a single bit is flipped?
  - Say, bit #3 changes from 0 to 1

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

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

- Now compute the parities on what you got
  - They come out to: ***0 1 1 1 0***
  - But in the message we have: ***1 0 1 1 0***
  - Error occurred!

But we get even more info

- Consider the parity bits alone
- Which bits didn't match?

0 1 1 1 0

1 0 1 1 0

- The first and second parity bits (p1 and p2)
- Add their positions up:
  - 1 + 2 = 3
- The error was in the third bit of the 20 bits
- So we can correct it!

Hamming

- Error detection
  - Detects 1 and 2 bit errors
- Error correction
  - Corrects all 1 bit errors
    - If more than one parity set is wrong, the parity numbers indicate the incorrect bit position
    - If only one parity set is wrong, then that parity bit itself is incorrect
- Cost:
  - $\log_2 N$ overhead
- Limits:
  - Cannot correct more than one error

Reed-Solomon

- A lot more complicated...
  - No we're not going to walk through it
- Why interesting?
  - Add t bits of overhead
  - Detects up to t errors
  - Corrects up to $\left\lfloor \frac{t}{2} \right\rfloor$ errors
  - Works for burst (consecutive) errors too

Error vs. loss

- Error
  - Symbols are received, but not what was sent
- Loss
  - Nothing is received

How do you detect a loss?

The role of time

- The only way to detect loss
  - Timer expires
- Do you KNOW it was lost?
  - Nope. Maybe just late.

Dealing with loss

- So what do you do?
- At some point, assume loss occurred
  – Though perhaps it didn't
- Then fix it!
  – In a way that won't cause problems if you're wrong
- ARQ: Automatic Repeat-reQuest

ARQ

- Sender
  - Transmits info in blocks with IDs
  - Keeps copies and retransmits on request
- Receiver
  - Collects blocks and looks for missing IDs
    - Typically gaps within received sequence
  - Ask sender to help (*requires reverse channel*)
    - What do you say?
    - When do you say it?

ARQ variants

Negative feedback (NACK)

- Receiver reports the IDs lost
  - Explicit request to resend
  - The IDs *presumed* lost
  - Messages could just be late
- Sender resends those explicit requests
  - No sender timers

Positive feedback (ACK)

- Receiver reports the IDs received
  - Confirms receipt
  - Implicit request to resend
  - No receiver timers
- Sender resends IDs not reported
  - Looks for gaps
  - IDs *presumed* lost
  - IDs could be lost, but so could NACK be

Variants of ARQ

- Stop-and-go
  - Positive feedback (ACK)
  - ID is 1 bit
  - Send ACK when block is received
  - Also called “alternating bit”
- Go-back-N
  - Positive feedback (ACK)
  - ID is larger
  - Send ACK when block is received
  - Sender backs up to block after (ID+1) and resends
- Selective repeat
  - Positive and/or negative (ACK/NACK)
  - ID is large
  - Sender retransmits only individual lost blocks

Reordering as error

- When is a message lost?
  - Or just late?
- What happens when messages are out of order?
  - Buffer them and reorder
  - Should this be limited? HOW?

Basic components of a channel

- A signal to use to indicate symbols
- A media the signal propagates in
- A set of symbols
- A way to generate and receive symbols
- Direction

How to create signals?

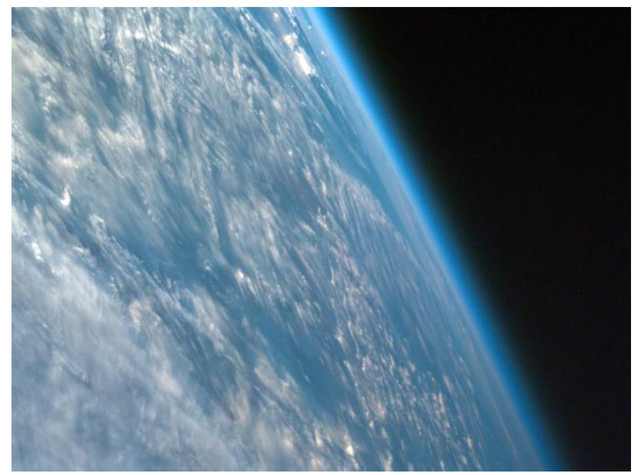
- Move photons
- Move electrons
- Move atoms
  - Motion waves (sound)
    - Pressure waves in gas, liquid
    - Transverse waves in solids
  - Streams of atoms (water flow)
- Move collections of atoms
  - Letters, flags, etc.

Types of media

- Unguided
  - Transparent
  - Mechanically conductive
- Guided
  - Transparent
  - Electrically conductive

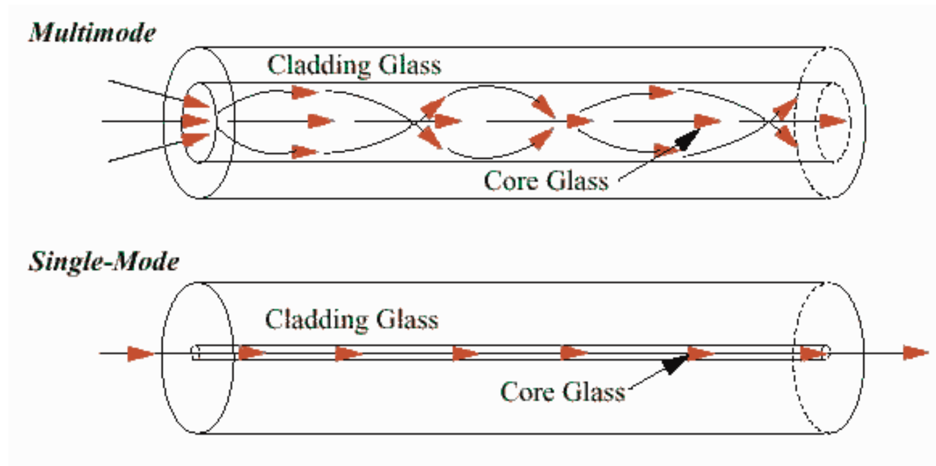
Freespace

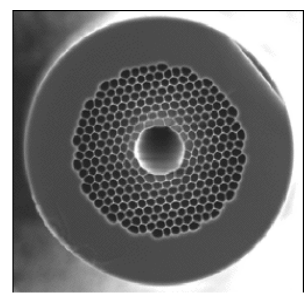
- Unguided
  - Transparent (includes vacuum)
  - Mechanically conductive (except a vacuum)
- Propagation velocity
  - Faster for EM
  - Slower for sound
- Signals degrade over distance
- Need a clear path
  - Not necessarily line-of-sight, though



Fibers

- Multi-mode
  - Thick core
  - Many paths
  - Many wavelengths
- Single-mode
  - Thin core
  - Fewer paths
  - Long-distance
- Hollow core
  - Uses air as the medium
  - Like freespace, but "guided"





Wires

- Guided
- Conductive
  – Material
    - Superconductors (various)
    - Silver, copper, gold, aluminum,…
- Number
  – Single-wire (ground-return)
  – Two-wire (direct return)

Communication symbols

- How we encode information on the signal
- Encodings do a lot for us
  - Represent information
  - Simplify generation
  - Simplify reception
  - Minimize errors

Some Example Encodings

- Amplitude shift keying
  - Use different signal power/strength values as symbols
- Return to zero
  - High/low signal value shows encoding
  - Signal value goes to zero between symbols
- Non-return to zero
  - Using common clock to encode/decode
- There are many others

Generating and interpreting signals

- Strictly:
  - *Generation* is a way to modulate non-varying sources to generate symbol pattern sequences that correspond to information patterns
- Practically:
  - *Generation* is a way to translate one symbol sequence into another
  - Since the source has its own representation of a sequence of symbols
- Interpretation is pretty much the same thing as generation
  - Just a different direction

Direction

- We're still talking about 2-party communication…
- Using a single channel, which of them can send to the other?

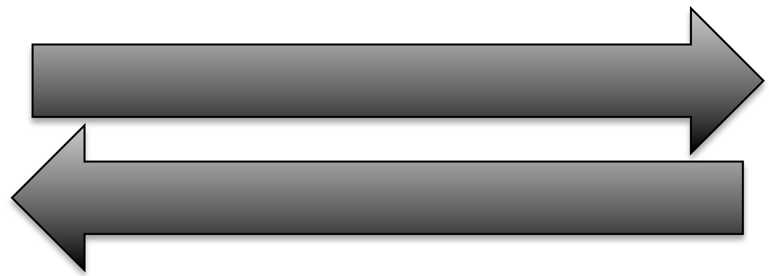
Simplex

- A channel transfers symbols in one direction only

- How?
  - Signal propagates in a medium

Duplex

- A channel simultaneously transfers symbols in both directions



- How?
  1. Using one natively bidirectional channel and transferring non-interfering particles
     - EM, e.g., photons or RF
  2. Using two simplex channels
     - One in each direction

Half-duplex

- Introduces sharing, but still 2-party
- How?
  - Using one natively bidirectional channel
  - Ensuring that the channel always contains only symbols travelling in the same direction
- How do we ensure that?
  - Need an automated mechanism to determine which end “speaks” next
  - One element of a protocol

What Is a Protocol?

- A set of rules, agreed in advance, that enable communication
  – *Endpoints*: the things that want to communicate
  – *Link:* enables action at a distance between the two endpoints
  – *Protocol*: specifies how to automate how these interact

How Do We Automate a Protocol?

- Use a *finite state machine*
  - One at each protocol participant, actually
- The "machine" is always in exactly one state
- There are a finite (and predefined) set of states
- Predefined actions cause transition from one of the states to another

Limits of FSMs

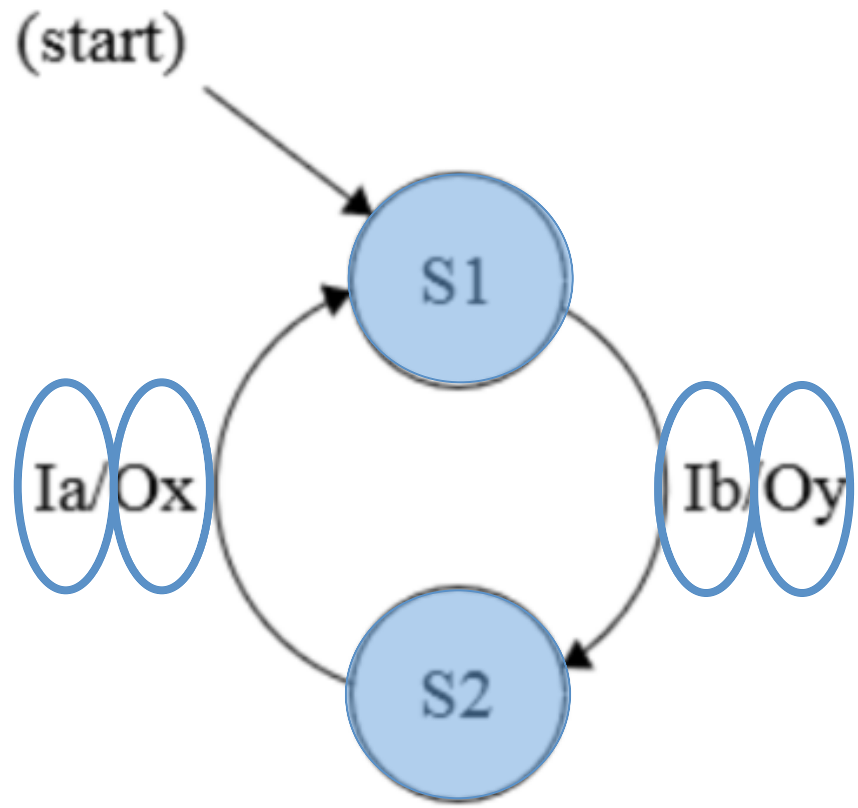
- Cannot count
  - Finite state, so limits on the count
- Cannot reverse or duplicate input
  - Duplicate would be:
    - AB -> ABAB
  - Reverse would be:
    - AB -> BA

Why do we want a FSM?

- Keep our state manageable!
- For networking, it's enough
  - We're basically playing "do what I do"

Mealy machine

- One type of FSM
- Has states (S)
- And transitions
  - Triggered by inputs (I)
  - Causing outputs (O)
- Generally a convenient type of FSM for networking



Sharing simple state for networking

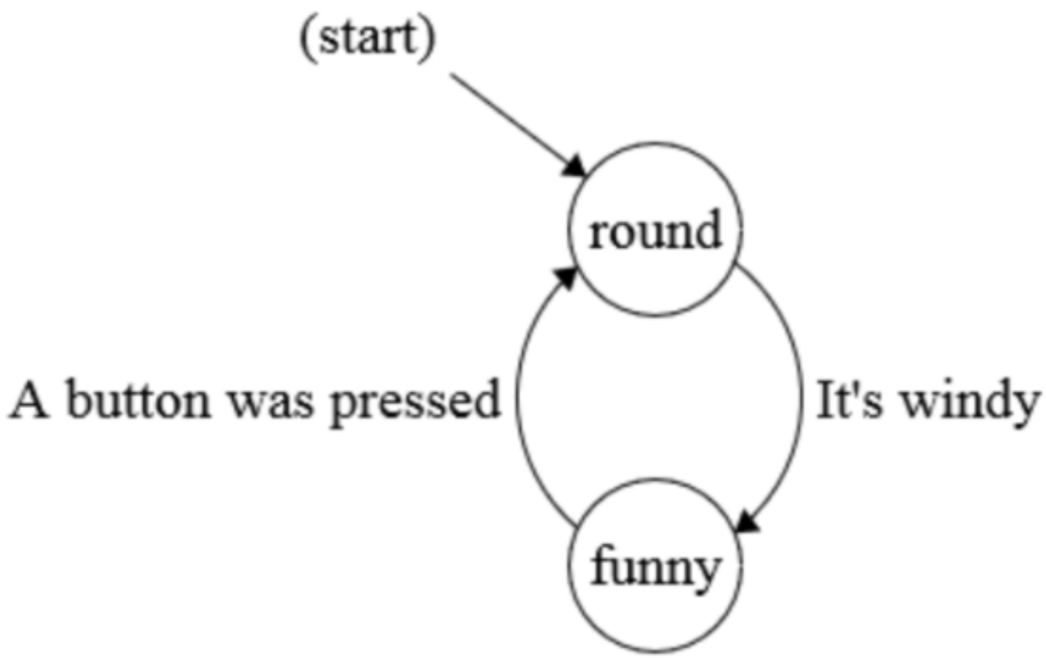
- A wants to communicate with B
  - The goal is for A and B to share state
- Assume a perfect channel
  - No errors, loss, reordering

Simplest state

- Simplest case:
  - Two states: "round" and "funny"
  - Do the names matter?
- A decides to be in one of two states.
  - The goal of communication is for A to make B in the same state.

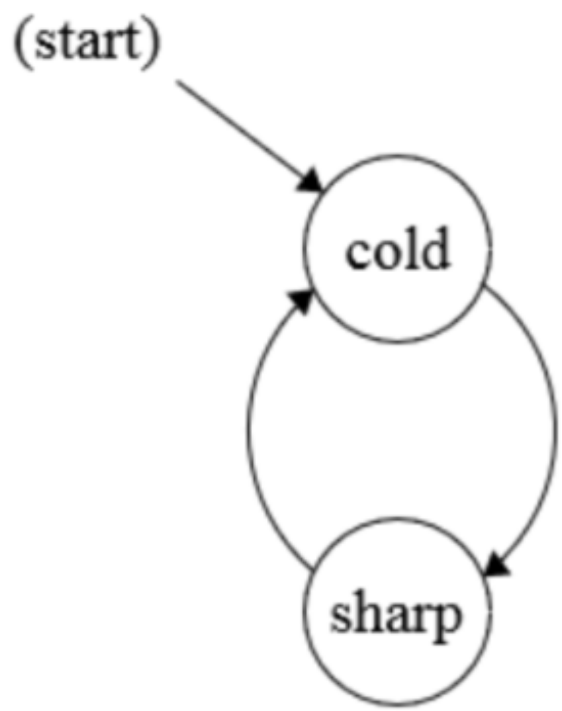
A gets to change state

- By itself, for some external reason



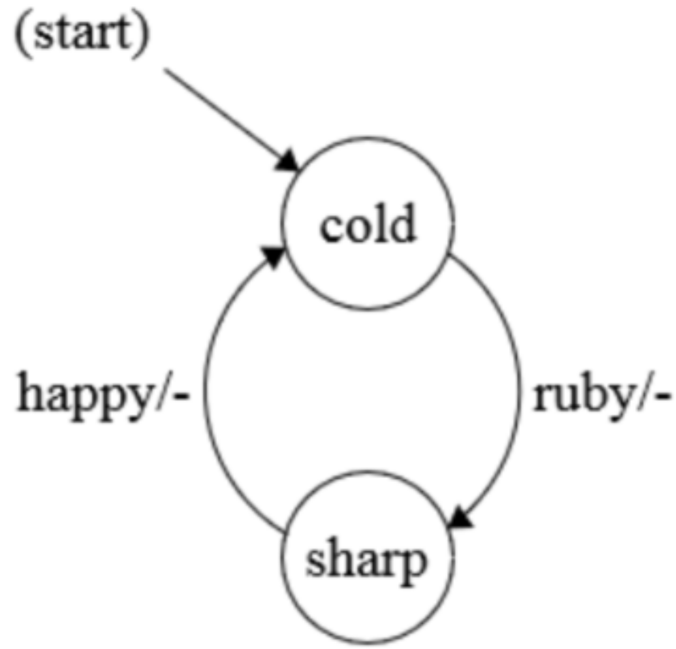
B has a similar state

- Names don't have to match



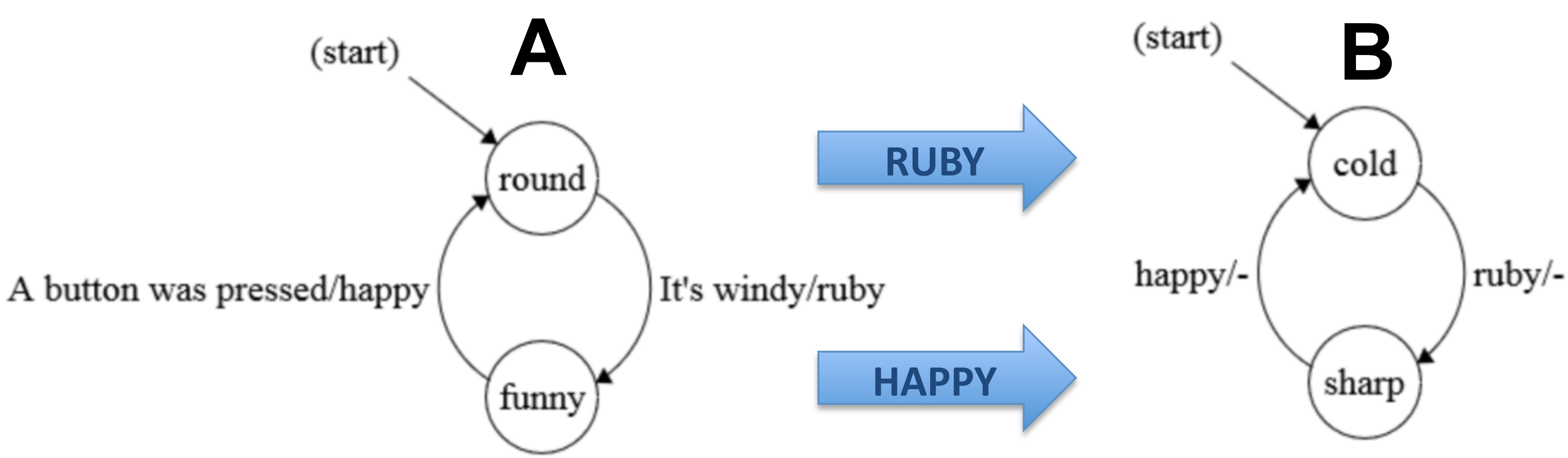
B gets to change state too

- Based on what it receives



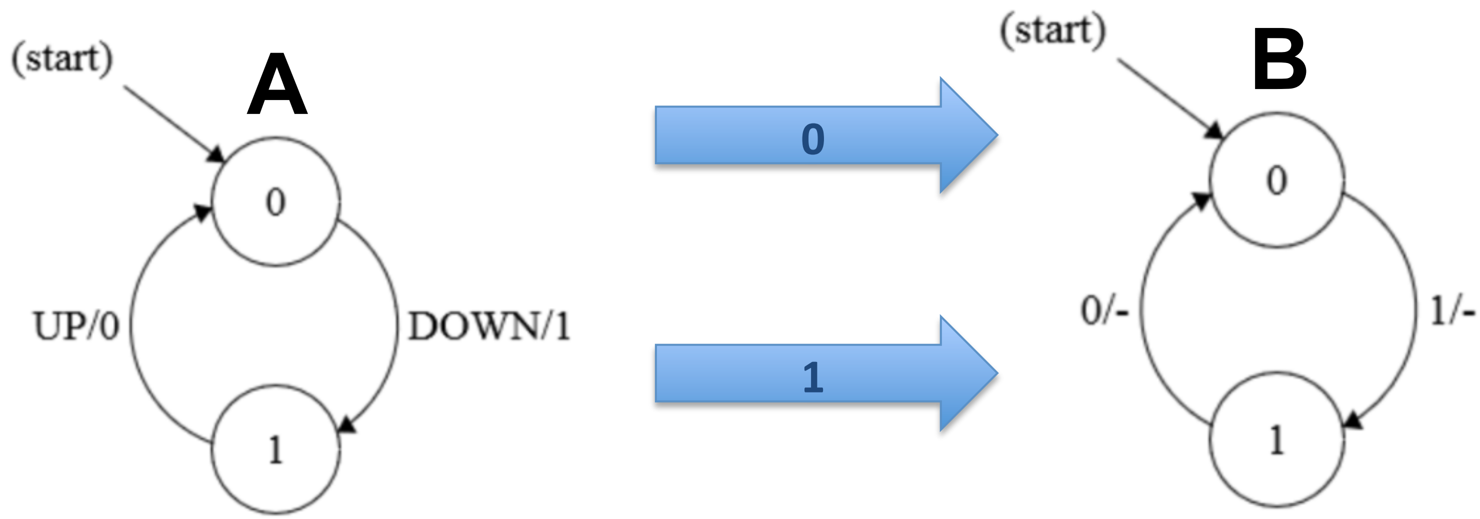
How do we communicate?

- Rules:
  - Every time A changes state, it let's B know
  - Every time B finds out, it changes state to match



Let's do that again, more simply

- A decides to toggle a switch UP or DOWN
  - Causes A to change state
  - Protocol makes B match A's state

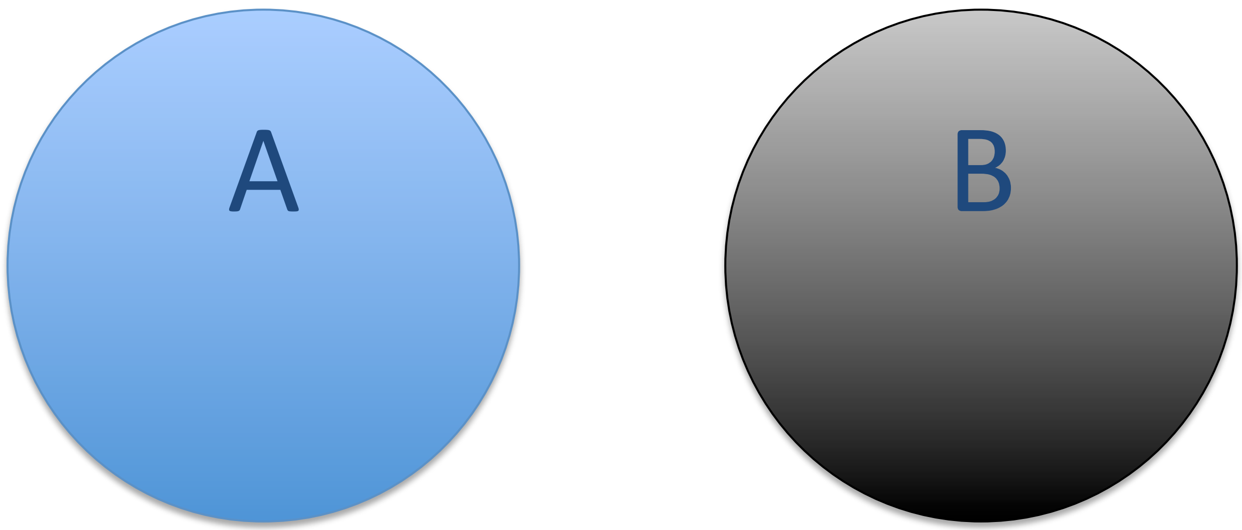


When are we done?

- When will the two states match?
  – Some time after A changes state, B will follow
- How long?
  – Who knows?
  – But it's a reliable channel, so it WILL change state eventually
  – Can we do better than that?

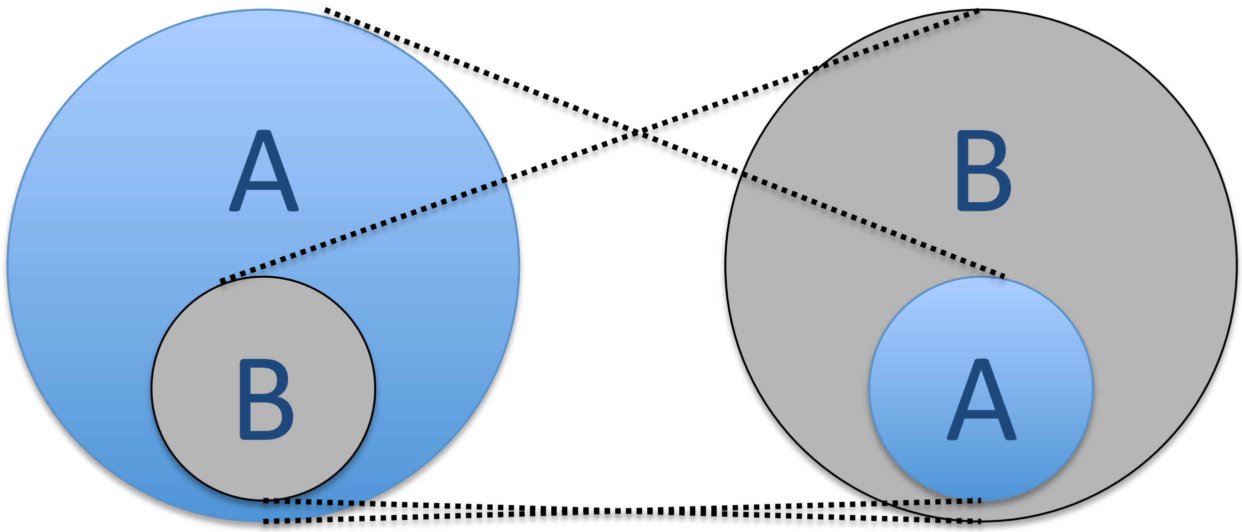
Mutual state

- States of A and B:



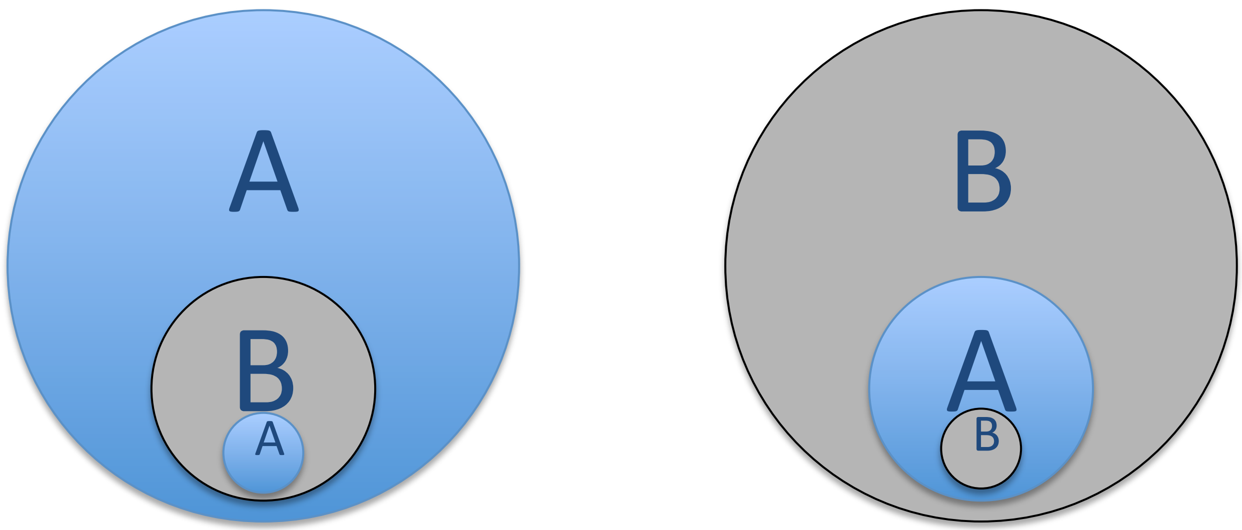
Mutual state

- States of A, B, A's view of B, B's view of A:



Mutual state

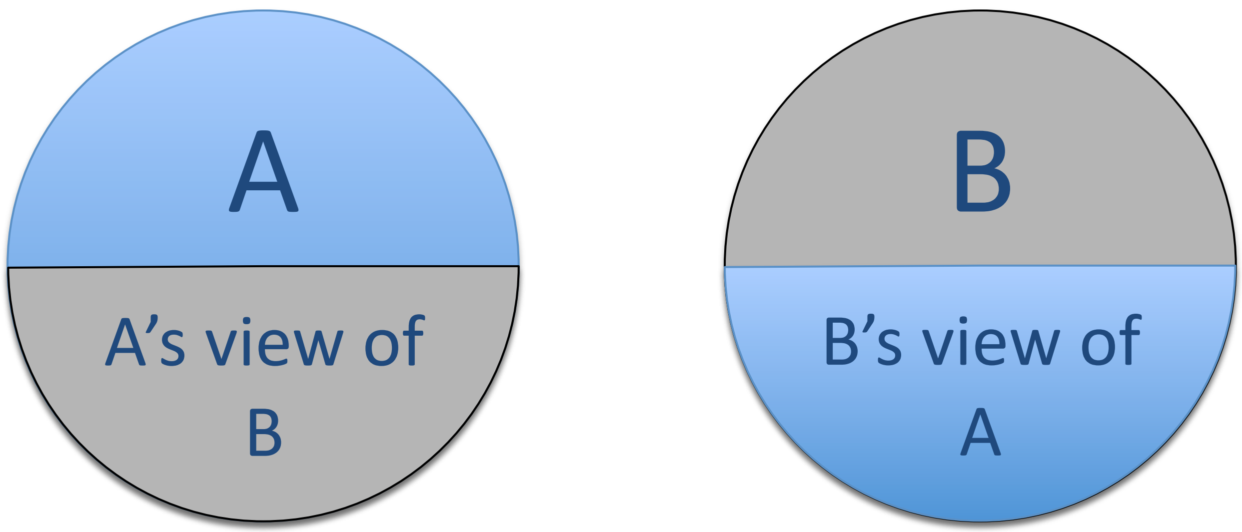
- Keep going!
  - No limit to the mutual modeling



Yikes!

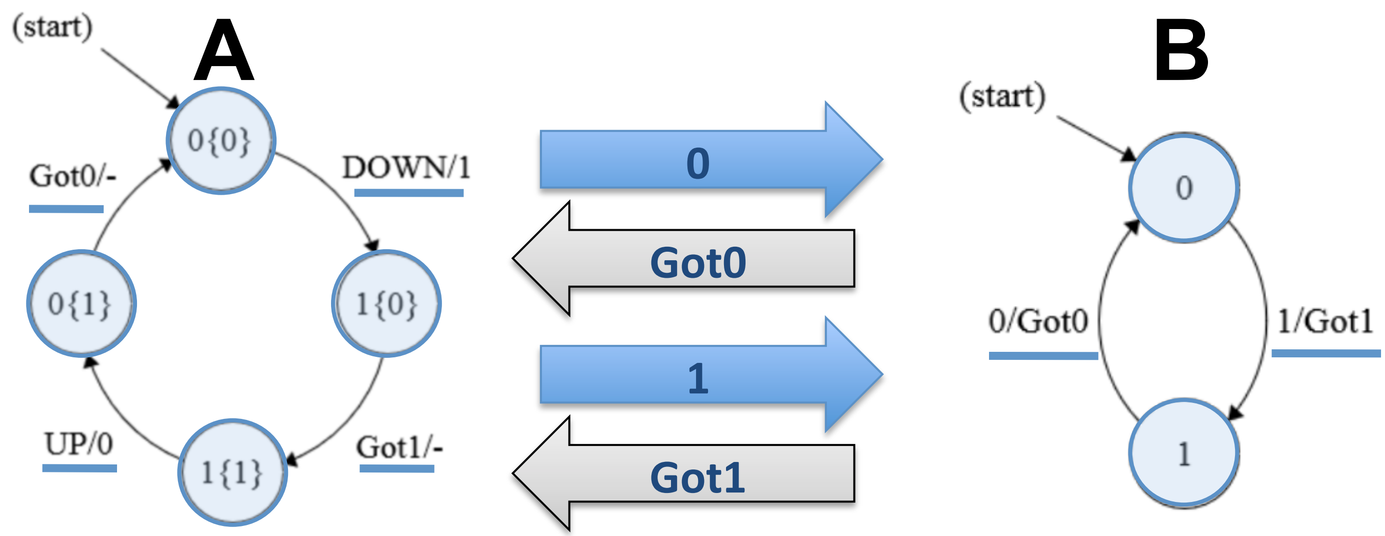
Limiting mutual state

- Stop at one step
  - Your state
  - Your view of the other end's state



Simple communication with confirmation

- Still sending info just from A to B
  - A models both sides
  - B confirms when it has changed state



Confirmation

- How does A know B learned of the state change?
- Positive acknowledgement
  - ACK
  - Confirms receipt of information

Complication #1: imperfection

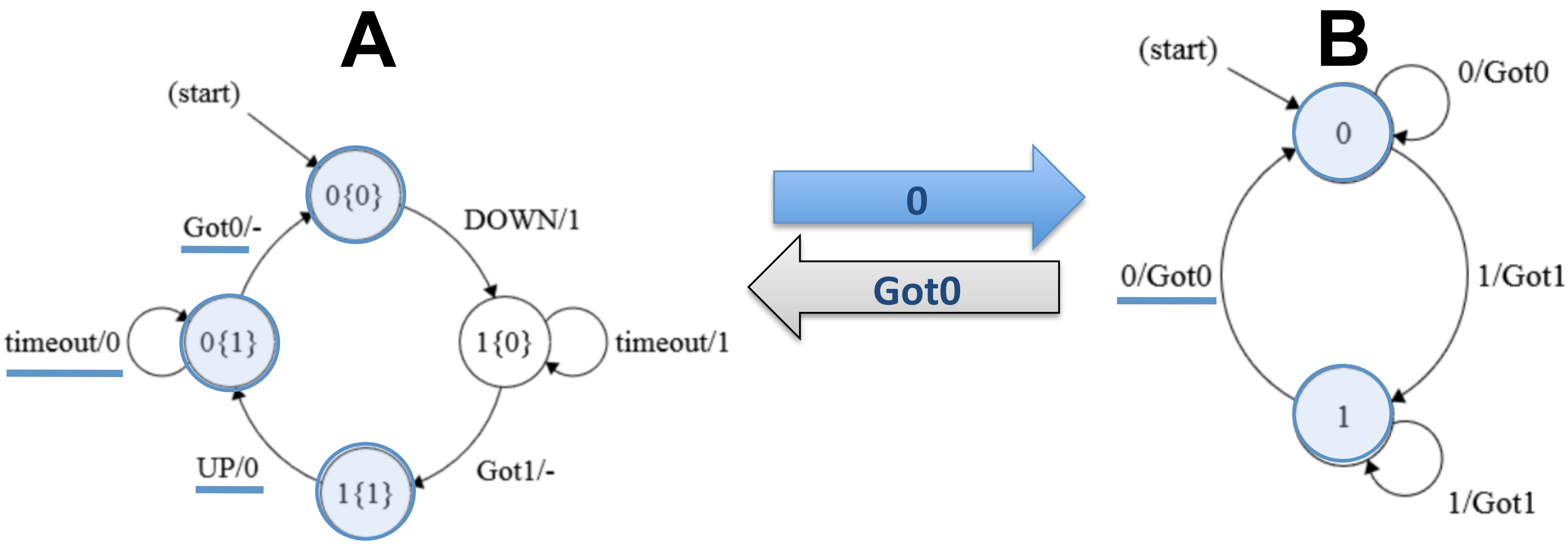
- Real channels aren't perfect
- Loss
  - Need to handle that
- Error
  - That can happen, too
  - But detect and address it as loss
  - Error you don't detect isn't an error (!)
    - It's the definition of your system . . .

How do we detect loss?

- Is it lost or just late?
- We can never know for sure
- We can only give up
  - When timer expires, we declare "loss"

Simple communication with loss

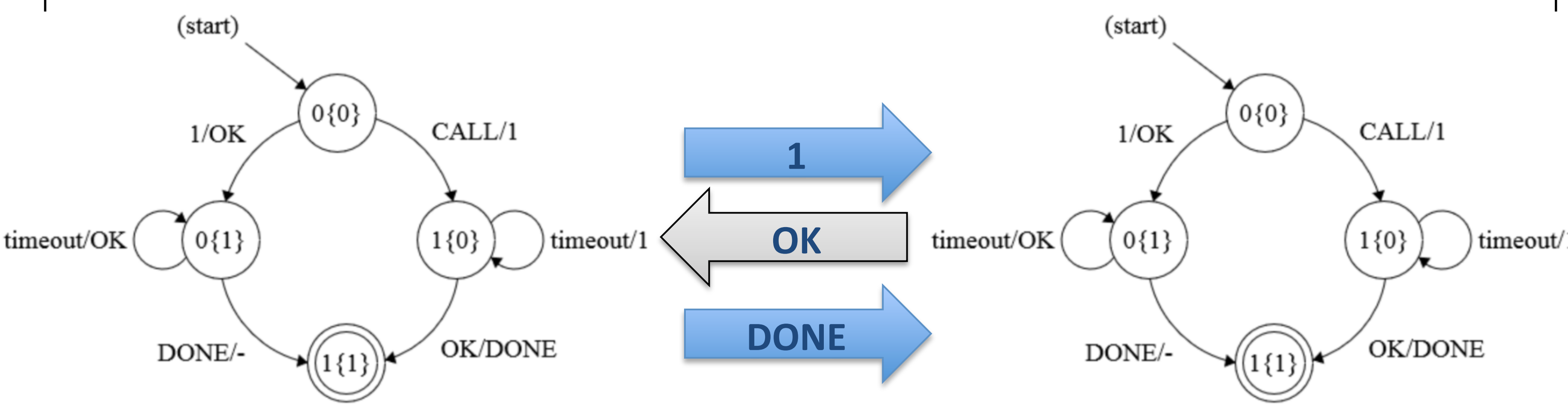
- Still sending info just from A to B
  - Add repeats based on timeouts



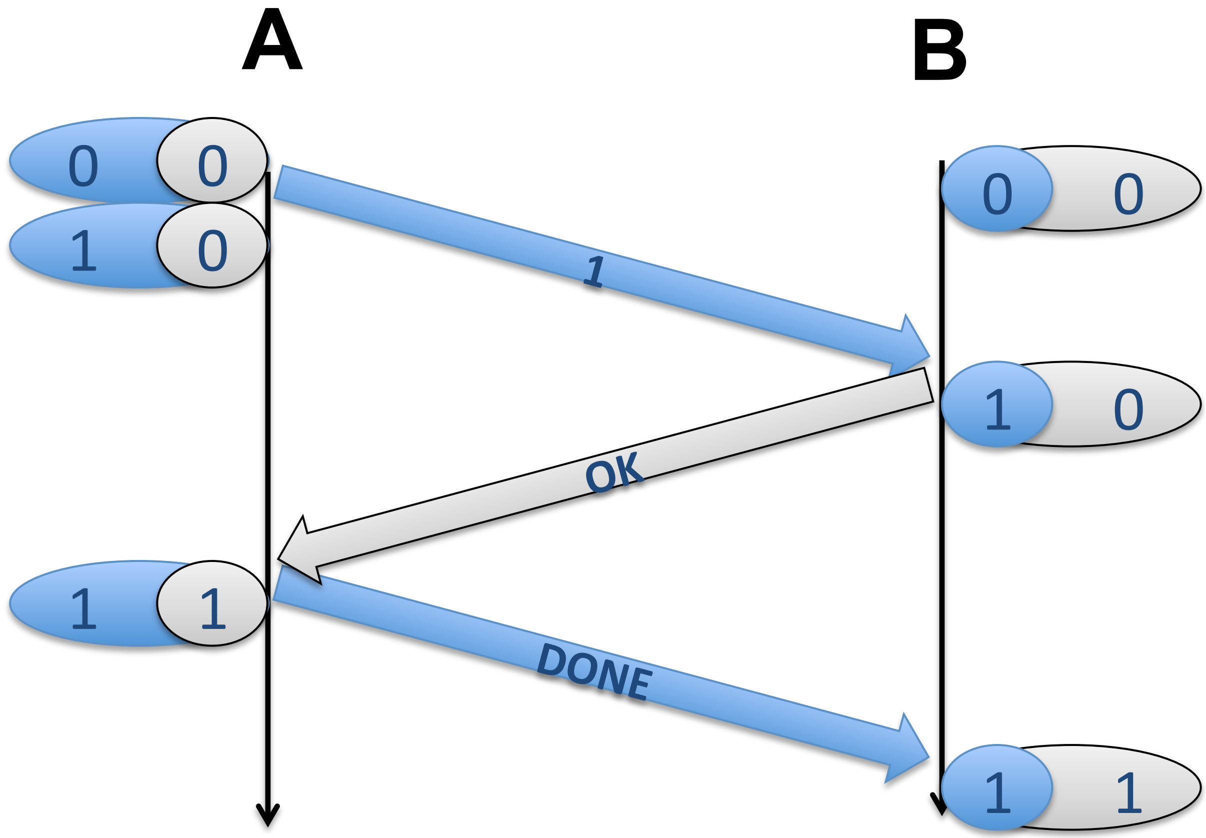
- But what if an ack is lost?

Time out on ACKs, too

- The three-way handshake (TWHS)

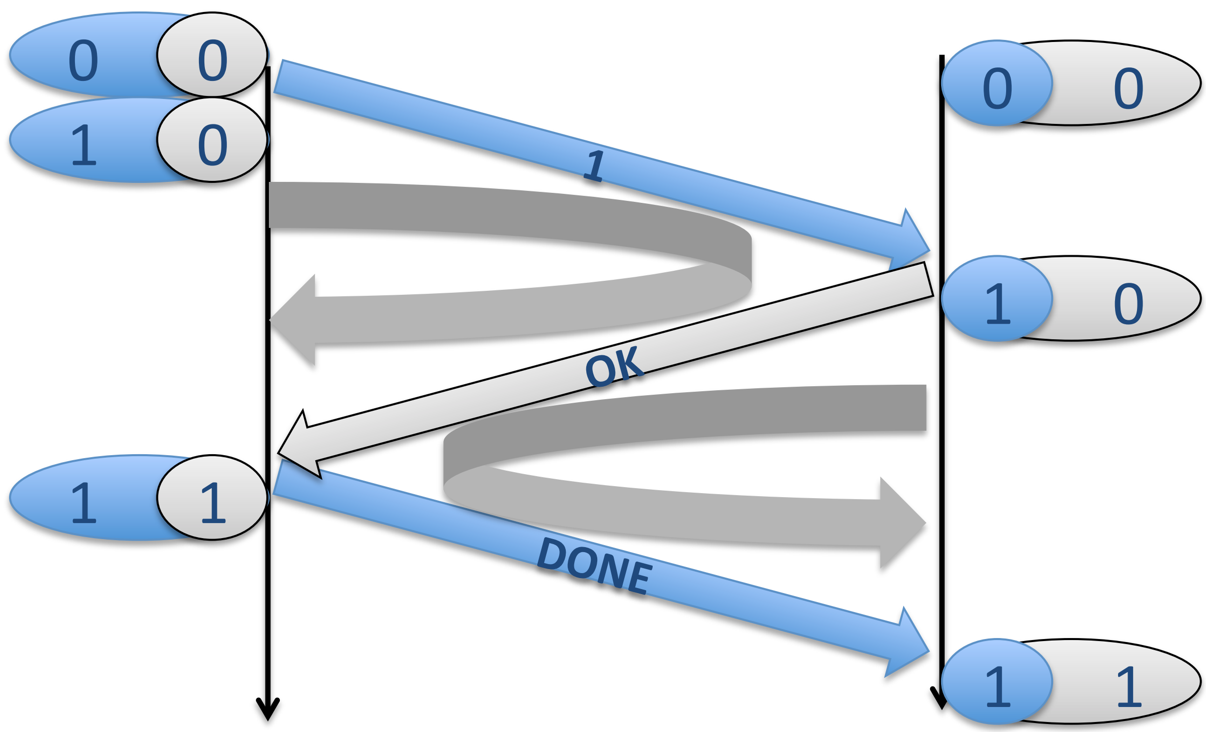


What's magic about TWHS?



What's magic about TWHS?

- Both sides have confirmed with each other



- We've achieved our limited mutual state

Specifying a protocol

- States
  - Endpoint values
- Symbols
  - Messages “on the wire”
- Events
  - Incoming
  - Outgoing
- Transition table
  - Relates the above
- All expressible as a state machine

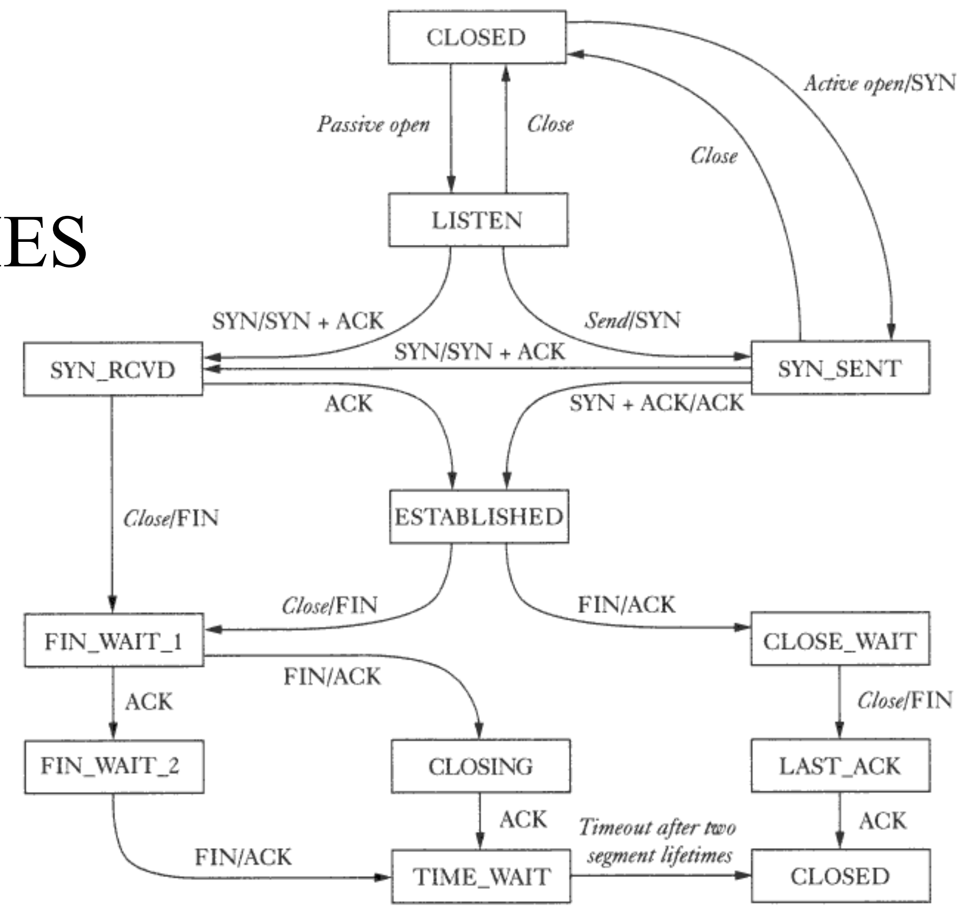
Let’s break that down a bit more

- States at the endpoints
- Symbols “on the wire”
- Events
  - IN:
    - Symbols received from the channel (receive) — Unix *receive()*
    - Symbols incoming at the sender — Unix *write()**
    - Timer expires
  - OUT:
    - Symbols sent on the channel (transmit) — Unix *send()*
    - Symbols out from the receiver — Unix *read()**
    - Timer is set
- Transition table
  - Maps events and states to other events and new states

* these are used from outside the protocol,
so *write()* is when an external process sends data into the protocol

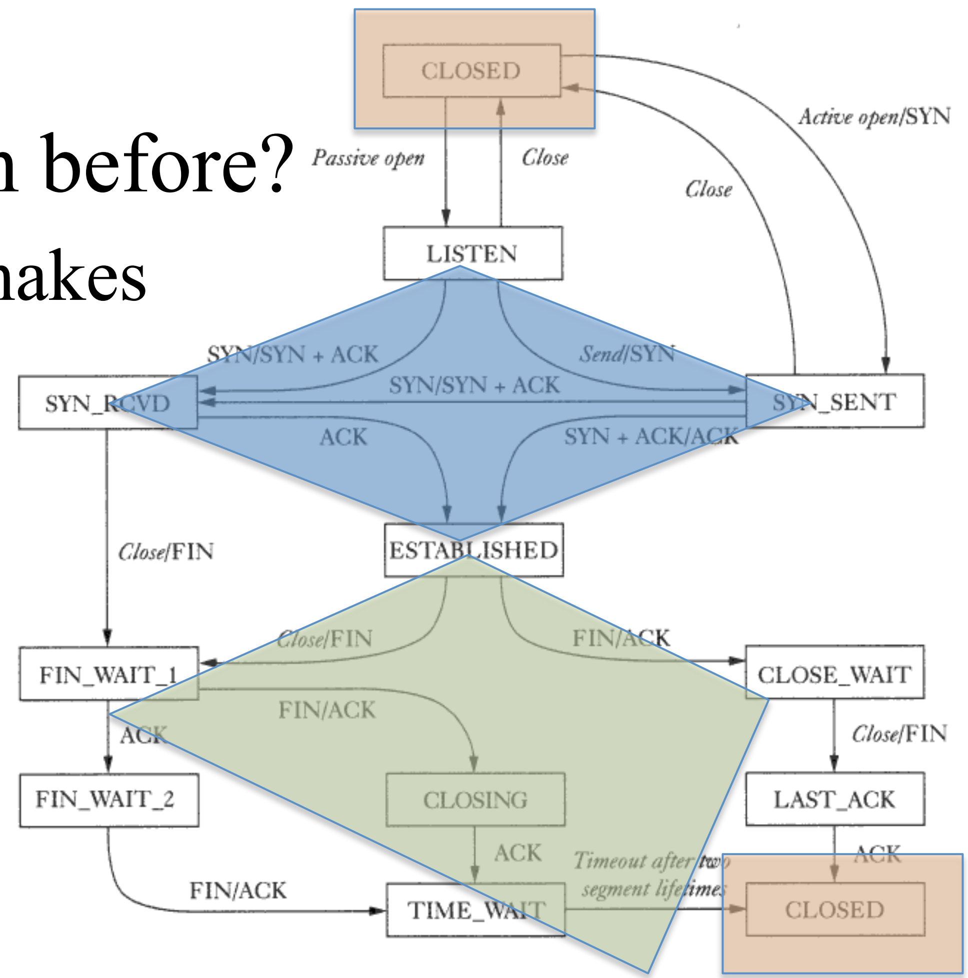
TCP state diagram

- Remember
  - They're just NAMES
  - It's the relation, not the name, that has meaning



This should look familiar

- What have we seen before?
  - Two sets of handshakes
- What's the rest?
  - "corner cases"



Complication #2: sharing complex state

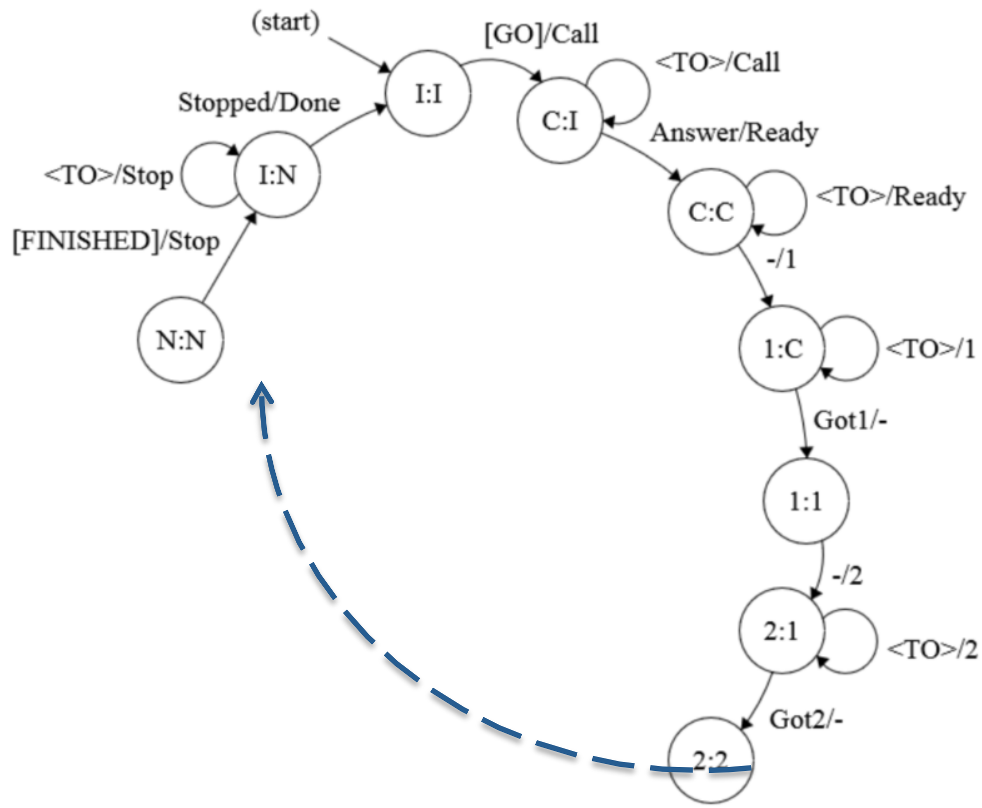
- What if we want to share more than one bit?
- Share bulk by “leap-of-faith”
  - Share a sequence of states

What's the leap of faith?

- We already know how to share *a* bit
- To share more:
  - First we agree on a first bit
    - We're both on the call
  - Then we agree on each block of bits sent
    - We're really agreeing on one bit:
      - Did you get *that* block?
      - "That" defined by an ID (sequence number) and checksum
  - Finally we agree we're done
  - We *assume* that if the above sequence is true, then the file was communicated correctly

Sequence of states

- Step through N items
  - Move forward once confirmed
  - Stepwise agreement
  - End with a final agreement



This 2-party stuff seems universal

- It is!
  - All protocols should be described the same way
    - States
    - Symbols (message formats)
    - Events
    - Transition tables
  - State diagrams have familiar parts
    - Three-way handshake
    - Confirmed shared state

Look at TCP

- States
  - Connection status
    - CLOSED, LISTEN, SYNSENT, SYNRECD, ESTABLISHED, …
    - Round-trip time, congestion window, …
  - Blocks transferred
    - Sequence number
- Symbols
  - SYN, FIN, RST, ACK
  - Block sequence ID
  - Data with checksum
- Events
  - Input
    - Message arrivals
    - Timer expires
    - Write events
  - Output
    - Message departure
    - Timer to set
    - Read events
- Transition table
  - State + inputevent -> newstate, outputevent

Why is it hard?

- Protocols can be large
  - Made of familiar parts
  - But many such parts
- There's more than 2 parties to consider
  - And we're getting to that soon too…

Summary

- Even noisy channels are useful
  - And we can calculate exactly how useful
- Errors happen
  - We can detect them
  - We can correct them
- We use protocols to automate communication
  - Which are implemented with finite state machines