BB84

Quantum *Protected* Cryptography

A.C.

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Outline

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- Maxwell's equations

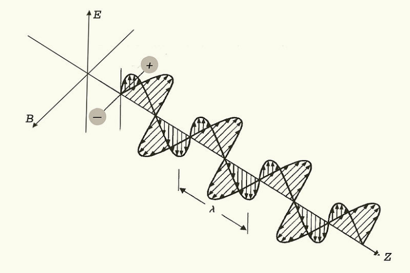
$$\oint_A EdA = \oint_A BdA = 0$$

$$\oint_C Edl = -\int_A \frac{\partial B}{\partial t} dA$$

$$\oint_C Bdl = \mu_0\epsilon \int_A \frac{\partial E}{\partial t} dA$$

Linearly Polarized Light

- Useful simplified model: assume harmonic, planar waves.
  - Between Fourier transforms and other superpositions this covers a surprising amount of ground.
  - Call the orientation of the E-wave the light's *polarization*



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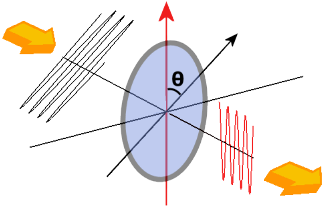
- Ideal polarizers follow Malus's law: $I = I_0 cos^2\theta$



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  - or possibly a superposition of different polarizations . . .
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- Instead polarizers absorb with probability $\sin^2\theta$
  - or transmit with probability $\cos^2\theta$

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- Observing a quantum entity, including photons, collapses it into a single state.
- Impossible to perfectly capture and reconstruct a photon of unknown polarization
  - Approximate cloning *is* possible, e.g. via stimulated emission
  - General upper bound on cloning fidelity of $\frac{5}{6}$
  - Fidelity bound for the case we'll care about of ≈ 0.8535

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- Bit flip with probability $\sin^2 \phi$, by Malus' law.

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7. If they observe a high rate of corruption, they start over.
8. Otherwise, the undropped and unannounced bits are now a shared secret.

Protocol in Pictures

Alice:	0	0	1	1	0	1	0	1

Alice selects random bits, bases

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Alice:	0	0	1	1	0	1	0	1
Bob:	?	?	?	?	?	?	?	?

Bob selects random bases

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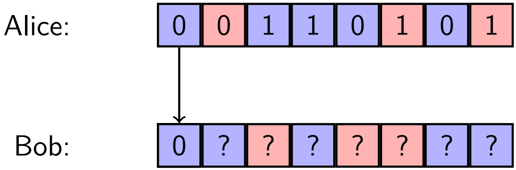

Bases agree, measurement succeeds

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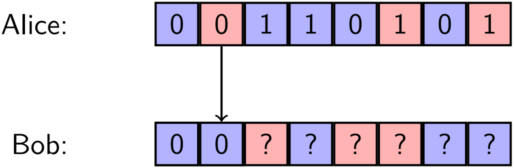

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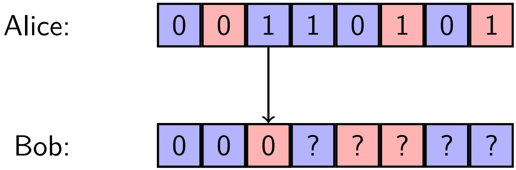

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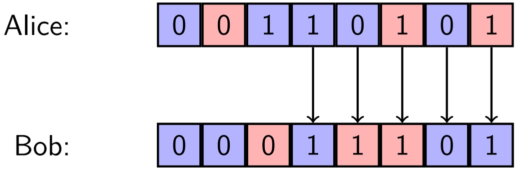

Etc...

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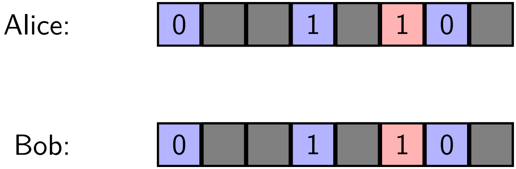

Sift out mismatched bases

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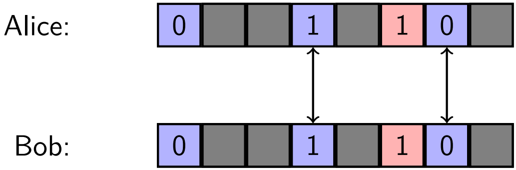

Sample bits to detect Eve

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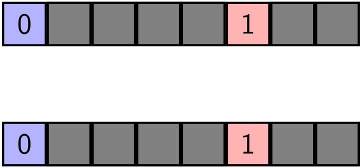
Bob:



Redact sampled bits

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- Can't stop Eve, but can *detect* her.

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- Even if Eve isn't interfering, some of our bits will be scrambled.
- Secrets which are mostly the same are not nearly as useful as secrets which are exactly the same.
- We need to somehow rectify the differences between what Alice sent and Bob received.

Single Error Detection

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  - How can we detect a lone bit flip?

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- Can write as a check matrix:

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  - Each parity bit will only cover some bits in the code word.
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- Hamming solved this for us in 1950 using powers of two
  - Code word: $(p_1, p_2, d_1, p_3, d_2, d_3, d_4)^T$
  - Check matrix:

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Full SECDED

- Glue a total parity bit onto a Hamming SEC scheme
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- Commonly known as Hamming(8,4).
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- We can reconcile errors by exchanging Hamming syndromes!

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7. Go back to (1) until convinced that the probability of surviving errors is negligible.

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- *Eve is allowed to have partial information on our secret!*
  - Or we can just never succeed in negotiating a secret
- Need to do two things
  - Estimate how many bits of information Eve has
  - Somehow scrub those bits out of our secret

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- Estimate $\hat{p} = \text{QBER}$?
  - Too easy to have $\hat{p} < p$
- Bayes rule to pick $\hat{p}$ s.t. $P(p > \hat{p}|\text{QBER}) < \epsilon$?
  - No sensible prior to put on p

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- Calculating CIs for a binomial distribution on the fly can be cumbersome
  - Common to pick m, p_{crit} in advance
  - Always trim off m bits, bail if $QBER > p_{\text{crit}}$

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- This is a direct result of the leftover hash lemma
- Approach is obvious:
  1. Alice publicly announces a random seed
  2. Alice and Bob both use the seed to hash their secrets down

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  - But we can still use the scheme to stretch the bootstrap secret, e.g. to allow for one-time pads in the data plane.
- Our goal is unconditional security, so a standard HMAC won't cut it.

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4. Discard the m bits used for the OTP.

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- The hash value is encrypted, so she can't manufacture a hash collision.
  - Universal hash function means she can't even make intelligent guesses about the hash value.
- Best she can do is guess the tag
  - Succeeds with probability $\frac{1}{2^m}$
  - Places a tradeoff between key expenditure and probability that Eve gets lucky.

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  - Bob expects a lot of transmissions to get lost, this won't necessarily set off alarm bells
- Attack is commonly known as photon number splitting

Decoy States

- Alice uses two (or more) signal sources S and S'
  - S is the real photon source, averages μ photons per pulse
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- Impossible for Eve to tell whether a given pulse came from S or S'

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  - S is the real photon source, averages μ photons per pulse
  - S' is a decoy, with $\mu' > \mu$
  - Upshot: S sends more single photon pulses than S'
- Impossible for Eve to tell whether a given pulse came from S or S'
- By blocking single photon pulses, Eve will affect the transmission rate for S more than for S'.

Decoy States

- Alice uses two (or more) signal sources S and S'
  - S is the real photon source, averages μ photons per pulse
  - S' is a decoy, with $\mu' > \mu$
  - Upshot: S sends more single photon pulses than S'
- Impossible for Eve to tell whether a given pulse came from S or S'
- By blocking single photon pulses, Eve will affect the transmission rate for S more than for S'.
- Alice and Bob can compare empirical transmission loss for S and S' at the end.
  - If they differ, they conclude Eve did something naughty.

TL;DR

1. Send/receive a stream of quanta in random bases.
2. Throw away the bits where bases disagreed.
3. Reconcile keys using (adaptations of) standard error correction schemes.
4. Hash your keys down according to pessimistic estimates of how much information Eve could have.
5. Make sure to authenticate all your messages throughout.
6. Profit!

References and Additional Materials

- Presentation source: https://github.com/alan-christopher/bb84/tree/master/edu
- Quantum Cryptography Intro: https://arxiv.org/abs/1002.1237
- Quantum Cloning: https://arxiv.org/abs/quant-ph/0511088
- Privacy Amplification: https://link.springer.com/article/10.1007/BF00191318
- Winnow: https://arxiv.org/abs/quant-ph/0203096
- Decoy states: https://arxiv.org/abs/quant-ph/0211153
- A QKD implementation: https://arxiv.org/abs/1603.08387

Included Works

- Transverse Wave Image
- Polarizer Image

Questions?