Quantum Cryptography

Christian Schaffner

QuSoft Research Center for Quantum Software

Institute for Logic, Language and Computation (ILLC)
University of Amsterdam

CWI Centrum Wiskunde & Informatica

AwesomeIT 2016, Amsterdam
Friday, 8 April 2016

NWO
Nederlandse Organisatie voor
Wetenschappelijk Onderzoek

1969: Man on the Moon

http://www.unmuseum.org/moonhoax.htm

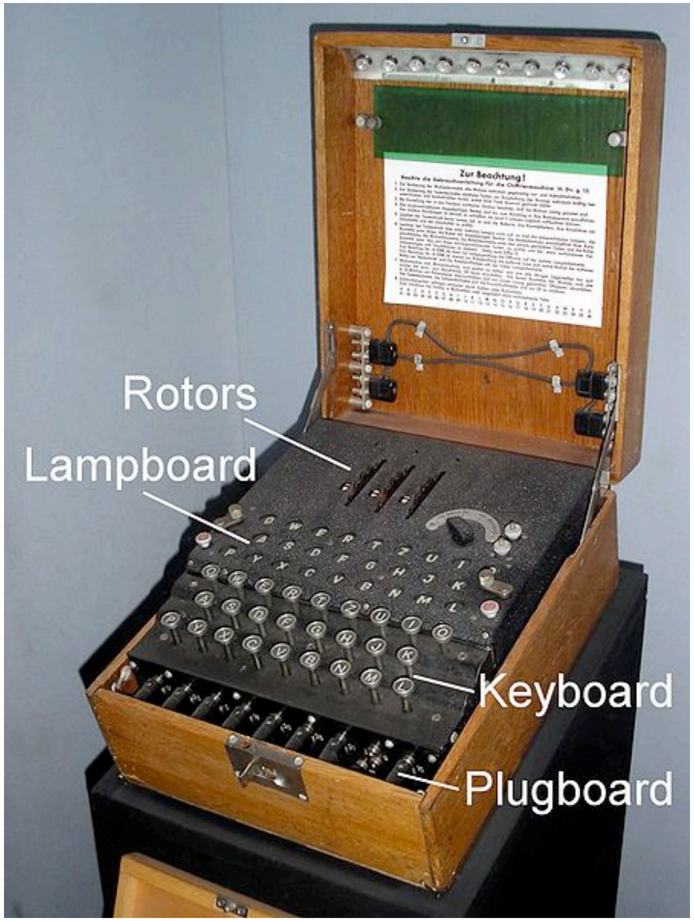
- How can you prove that you are at a specific location?

What will you learn from this Talk?

- Classical Cryptography
- Introduction to Quantum Mechanics
- Quantum Key Distribution
- Position-Based Cryptography

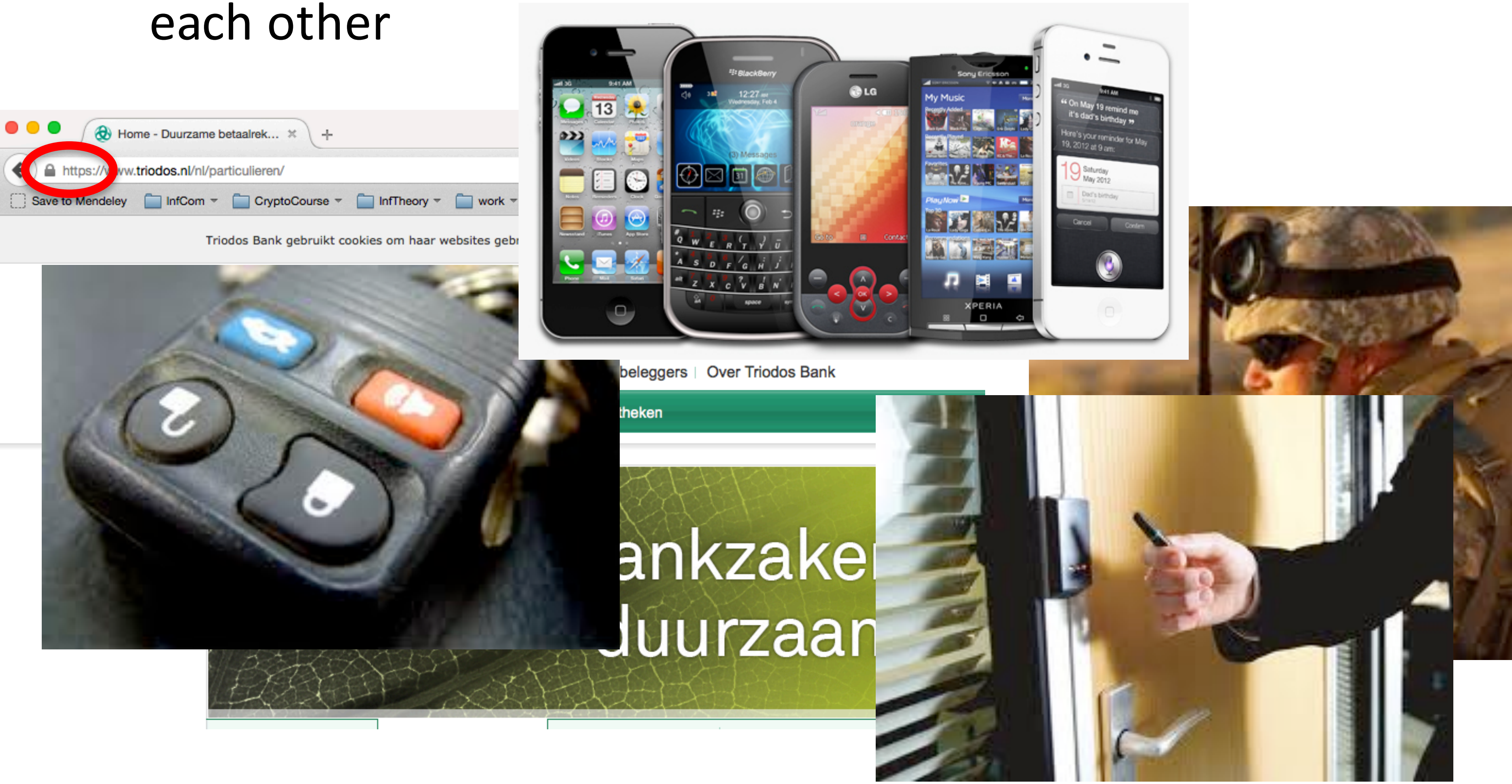
Ancient Cryptography

- 3000 years of fascinating history
- until 1970: private communication was the only goal



Modern Cryptography

- is everywhere!
- is concerned with all settings where people do not trust each other

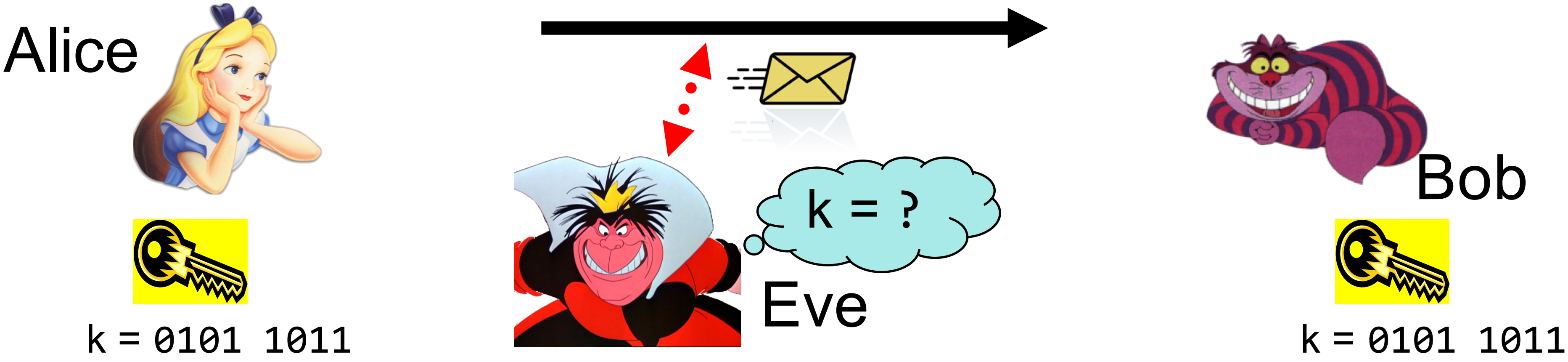


Triodos Bank gebruikt cookies om haar websites gebr

Secure Encryption

m = “I love you”

m = 0000 1011



k = 0101 1011

k = 0101 1011

- Goal: Eve does not learn the message
- Setting: Alice and Bob share a secret key k

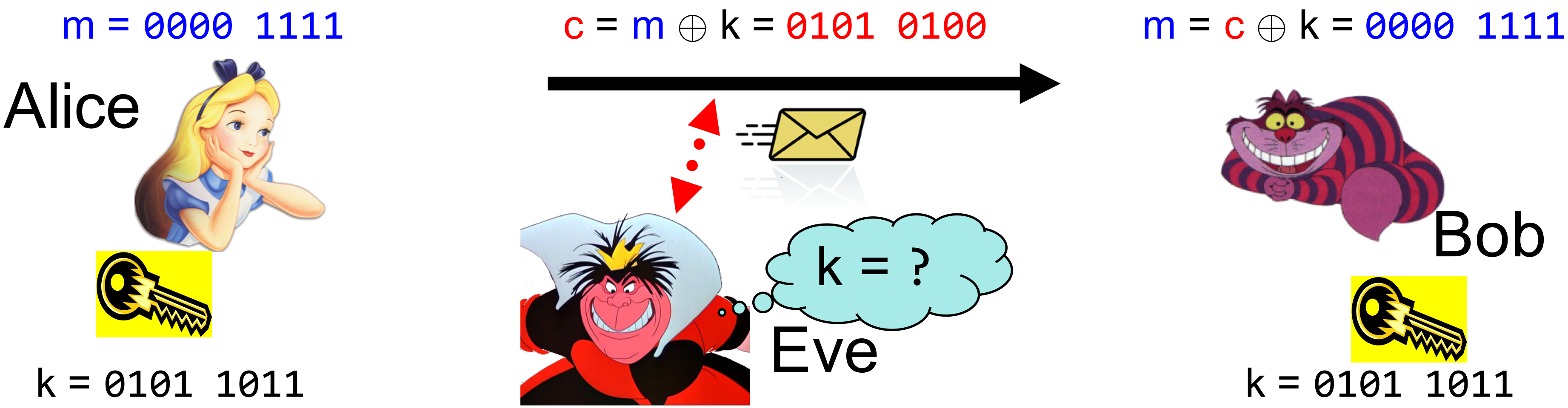
eXclusive OR (XOR) Function

x	y	$x \oplus y$
0	0	0
1	0	1
0	1	1
1	1	0

- Some properties:
  - $\forall x : x \oplus 0 = x$
  - $\forall x : x \oplus x = 0$

$\Rightarrow \forall x,y : x \oplus y \oplus y = x$

One-Time Pad Encryption



m = 0000 1111

c = m $\oplus$ k = 0101 0100

m = c $\oplus$ k = 0000 1111

Alice

k = 0101 1011

Eve

Bob

k = 0101 1011

- Goal: Eve does not learn the message
- Setting: Alice and Bob share a key k
- Recipe:

m = 0000 1111

k = 0101 1011

c = m $\oplus$ k = 0101 0100

c = 0101 0100

k = 0101 1011

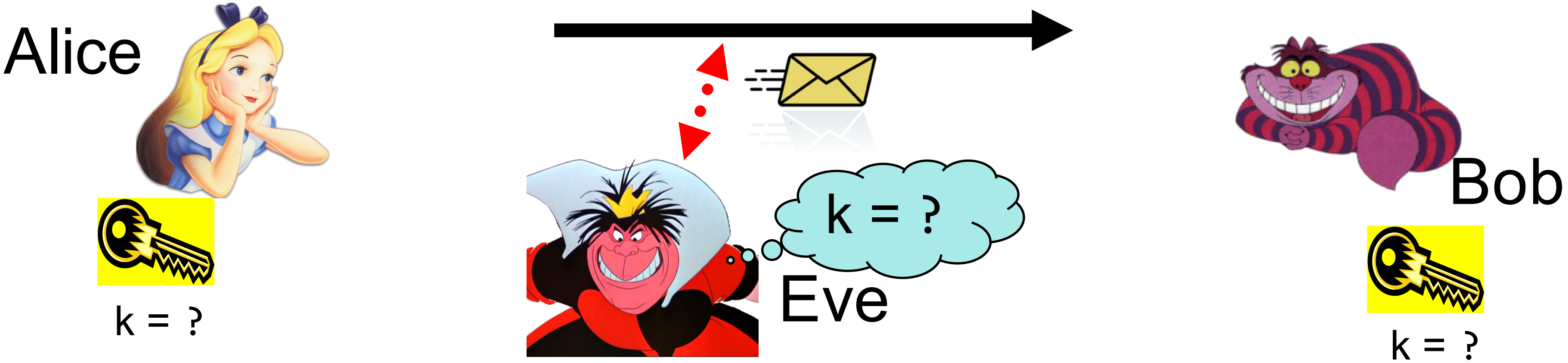
c $\oplus$ k = 0000 1111

c $\oplus$ k = m $\oplus$ k $\oplus$ k = m $\oplus$ 0 = m

x	y	x $\oplus$ y
0	0	0
0	1	1
1	0	1
1	1	0

- Is it secure?

Perfect Security



$m = ?$

$c = m \oplus k = 0101\ 0100$

$m = c \oplus k = ?$

Alice

$k = ?$

$k = ?$

Eve

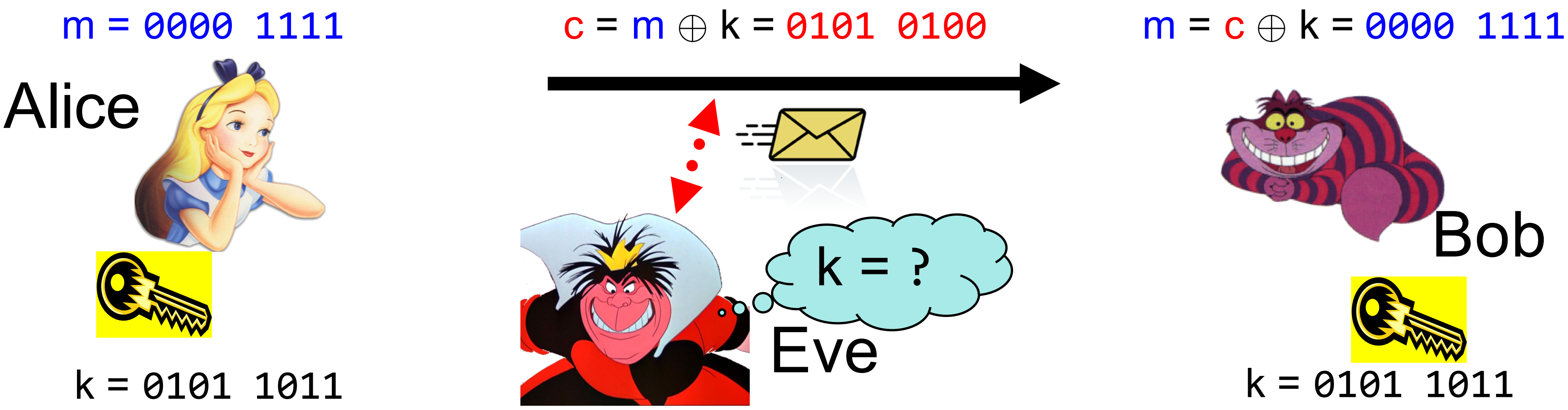
Bob

$k = ?$

- Given that $c = 0101\ 0100$,
  - is it possible that $m = 0000\ 0000$?
    - Yes, if $k = 0101\ 0100$.
  - is it possible that $m = 1111\ 1111$?
    - Yes, if $k = 1010\ 1011$.
  - it is possible that $m = 0101\ 0101$?
    - Yes, if $k = 0000\ 0001$
- In fact, every m is possible.
- Hence, the one-time pad is perfectly secure!

x	y	x ⊕ y
0	0	0
0	1	1
1	0	1
1	1	0

Problems With One-Time Pad



$m = 0000\ 1111$

$c = m \oplus k = 0101\ 0100$

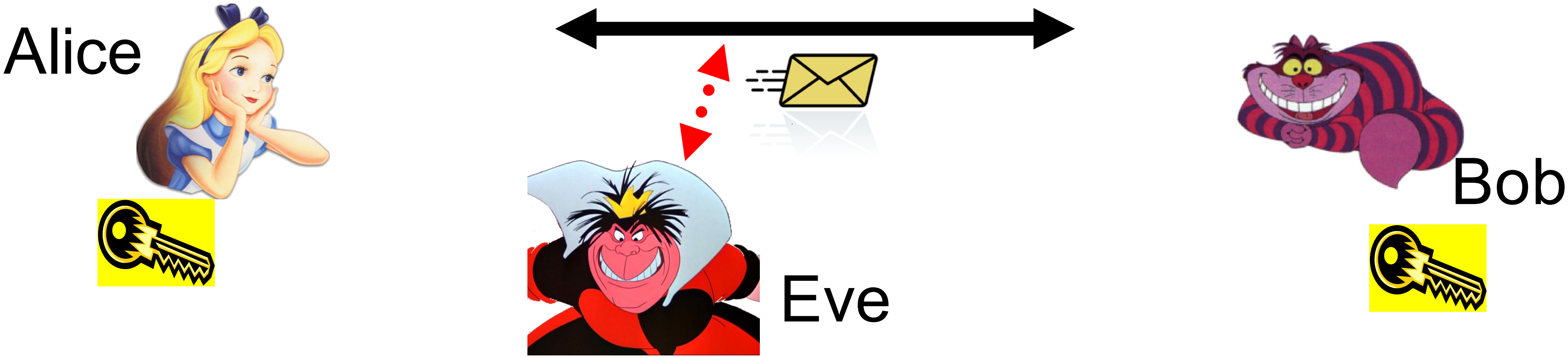
$m = c \oplus k = 0000\ 1111$

$k = 0101\ 1011$

$k = 0101\ 1011$

- The key has to be as long as the message (Shannon's theorem)
- The key can only be used once.
- In practice, other encryption schemes (such as AES) are used which allow to encrypt long messages with short keys.
- One-time pad does not provide authentication: Eve can easily flip bits in the message

Symmetric-Key Cryptography



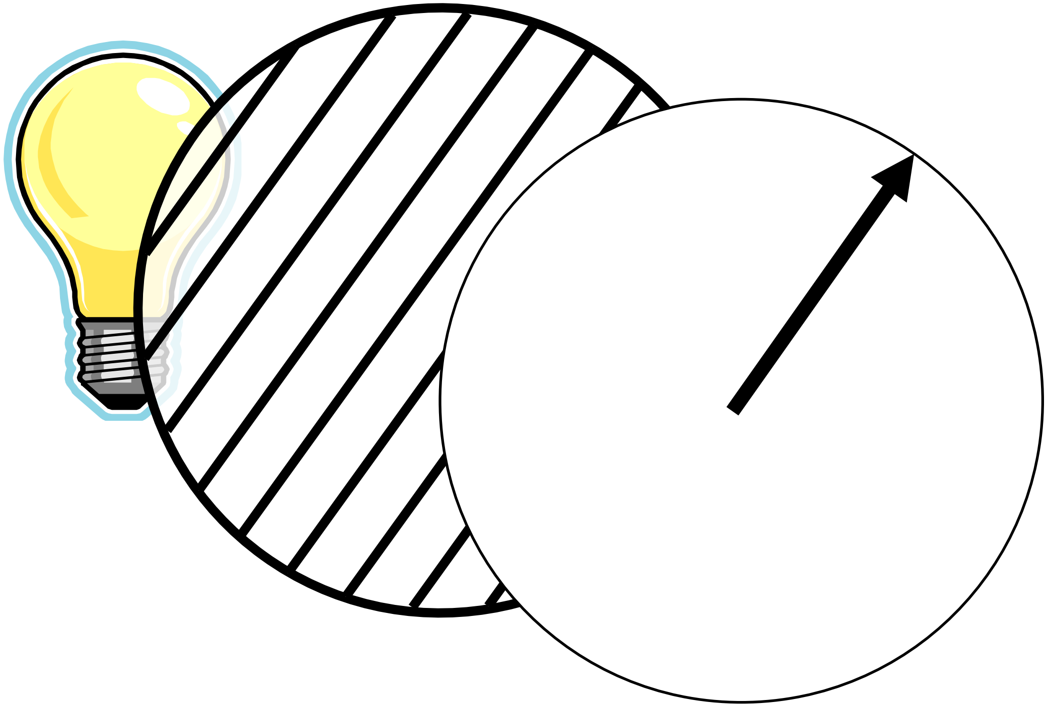
- Encryption insures secrecy:
  Eve does not learn the message, e.g. one-time pad
- Authentication insures integrity:
  Eve cannot alter the message
- General problem: players have to exchange a key to start with

What will you Learn from this Talk?

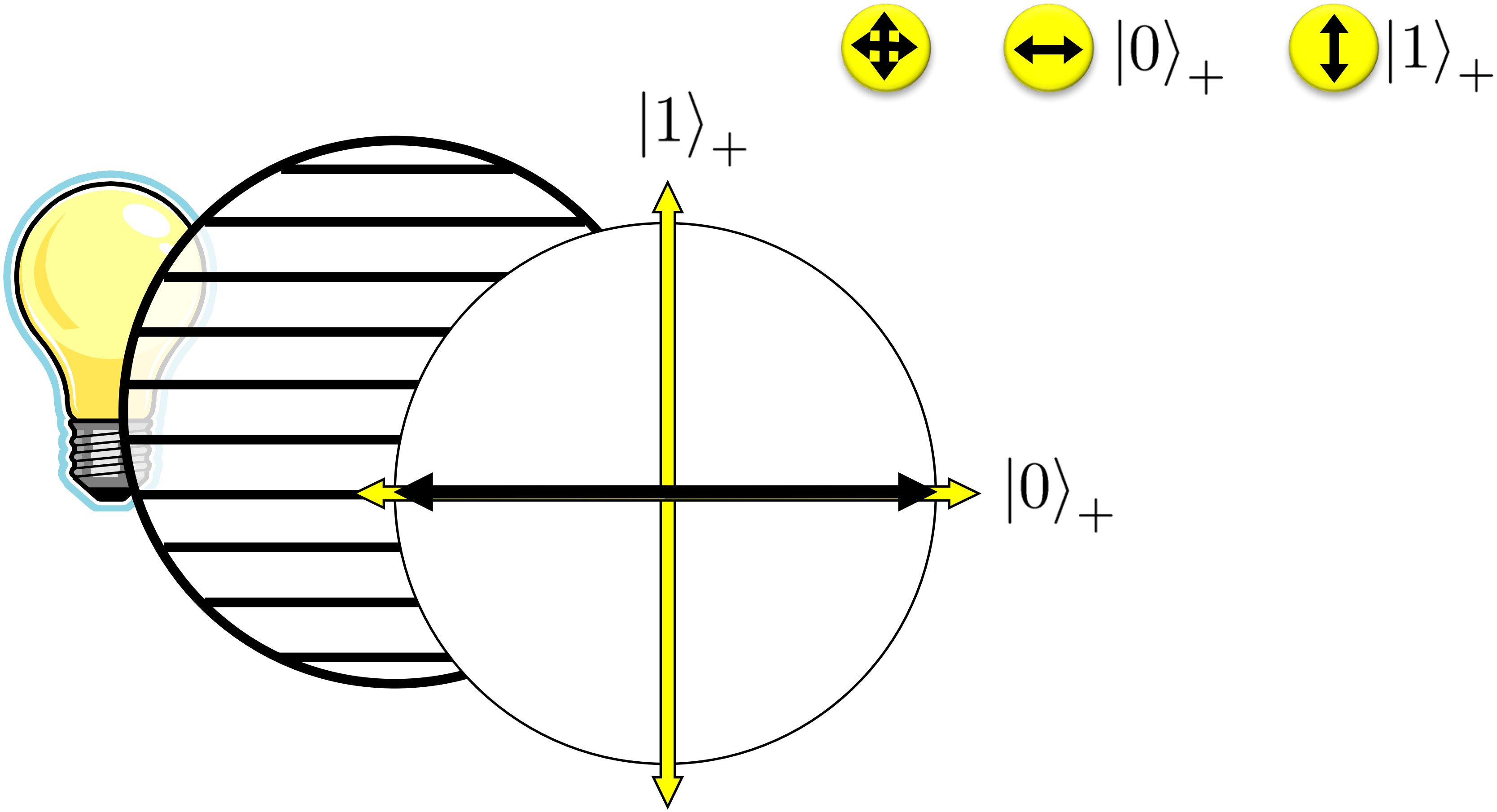
- ✓ Classical Cryptography
- Introduction to Quantum Mechanics
- Quantum Key Distribution
- Position-Based Cryptography

Quantum Bit: Polarization of a Photon

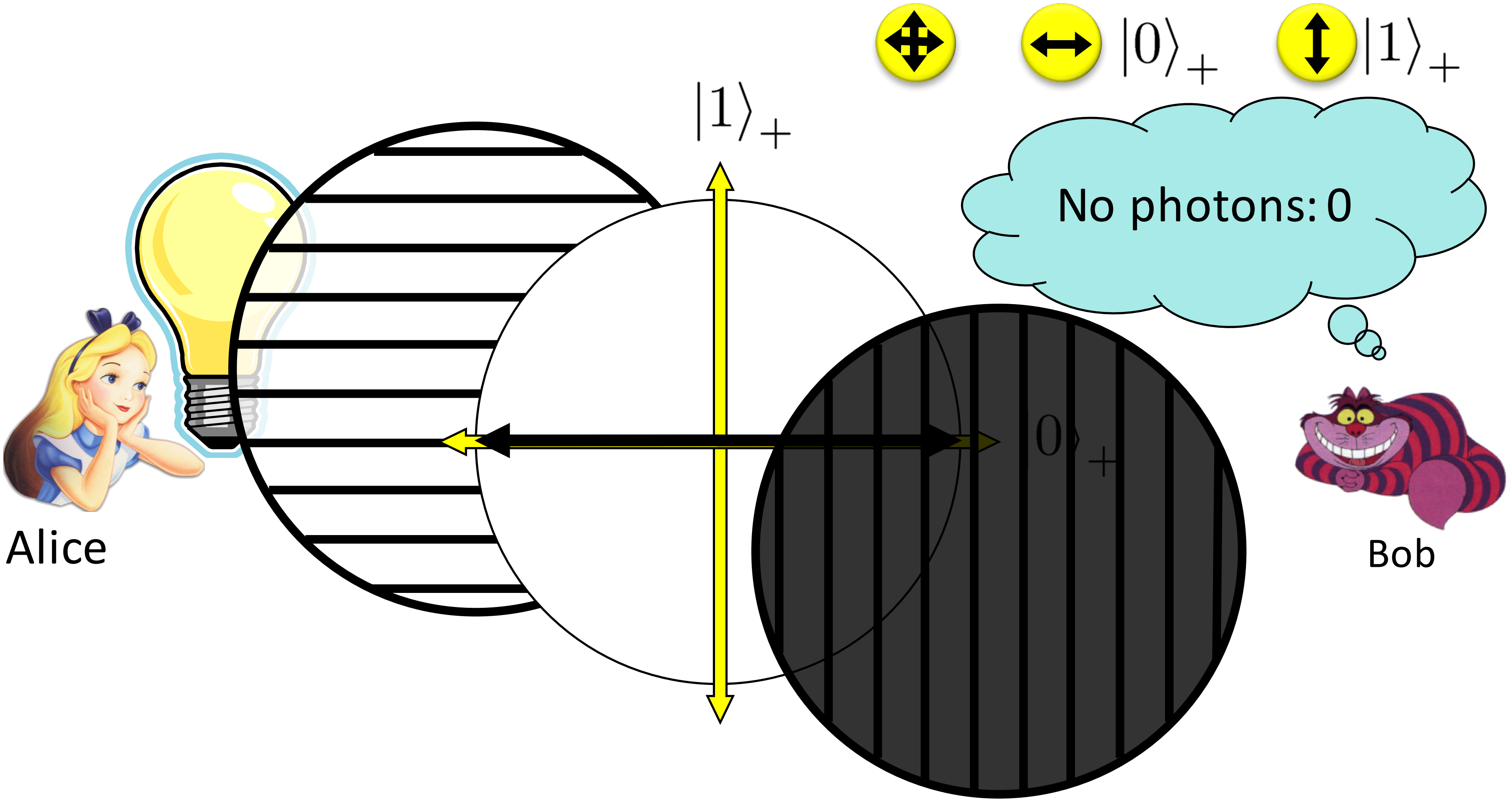
qubit as unit vector in $\mathbb{C}^2$



Qubit: Rectilinear/Computational Basis



Detecting a Qubit



$|0\rangle_+$ $|1\rangle_+$

$|1\rangle_+$

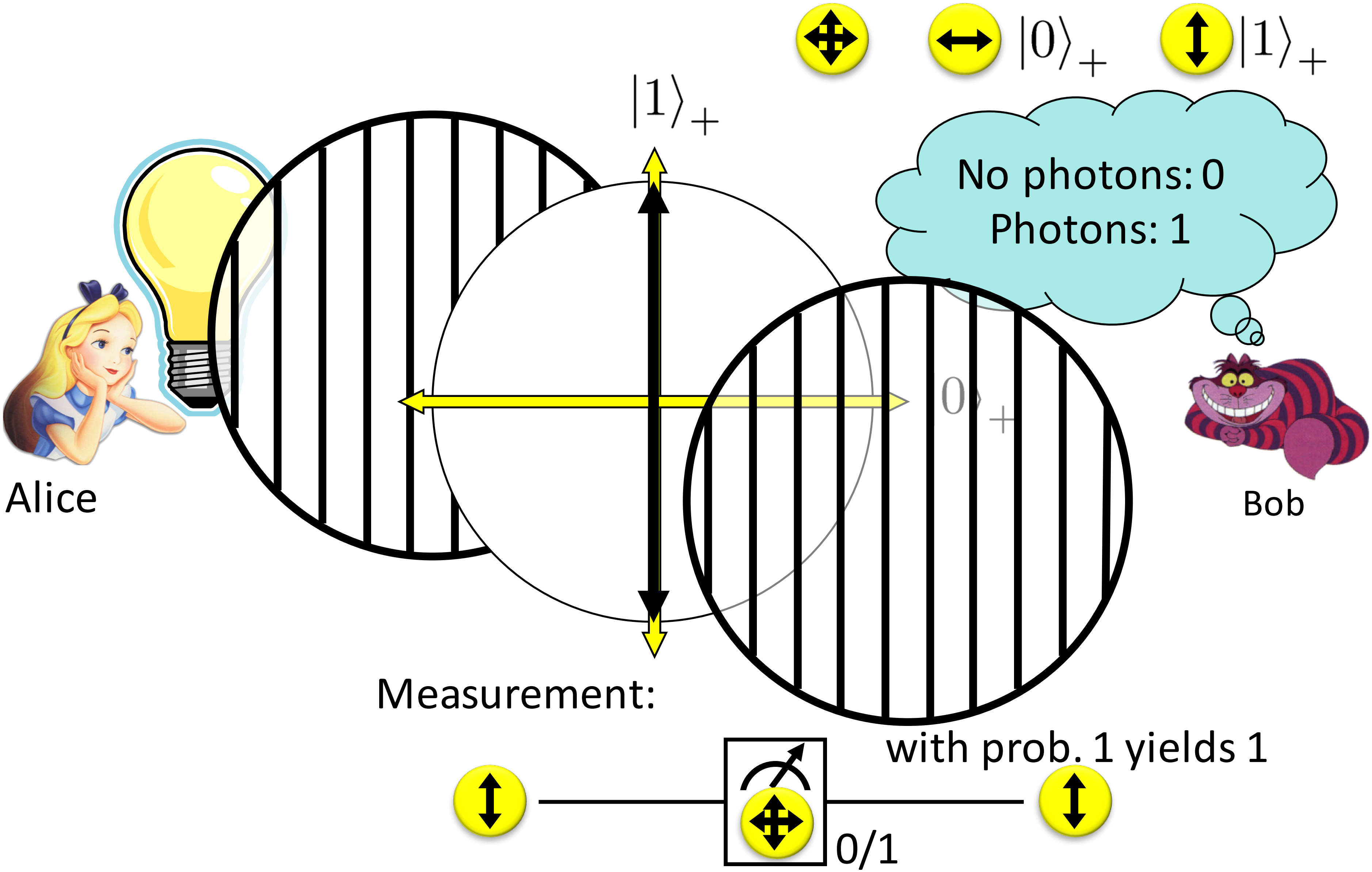
No photons: 0

$|0\rangle_+$

Alice

Bob

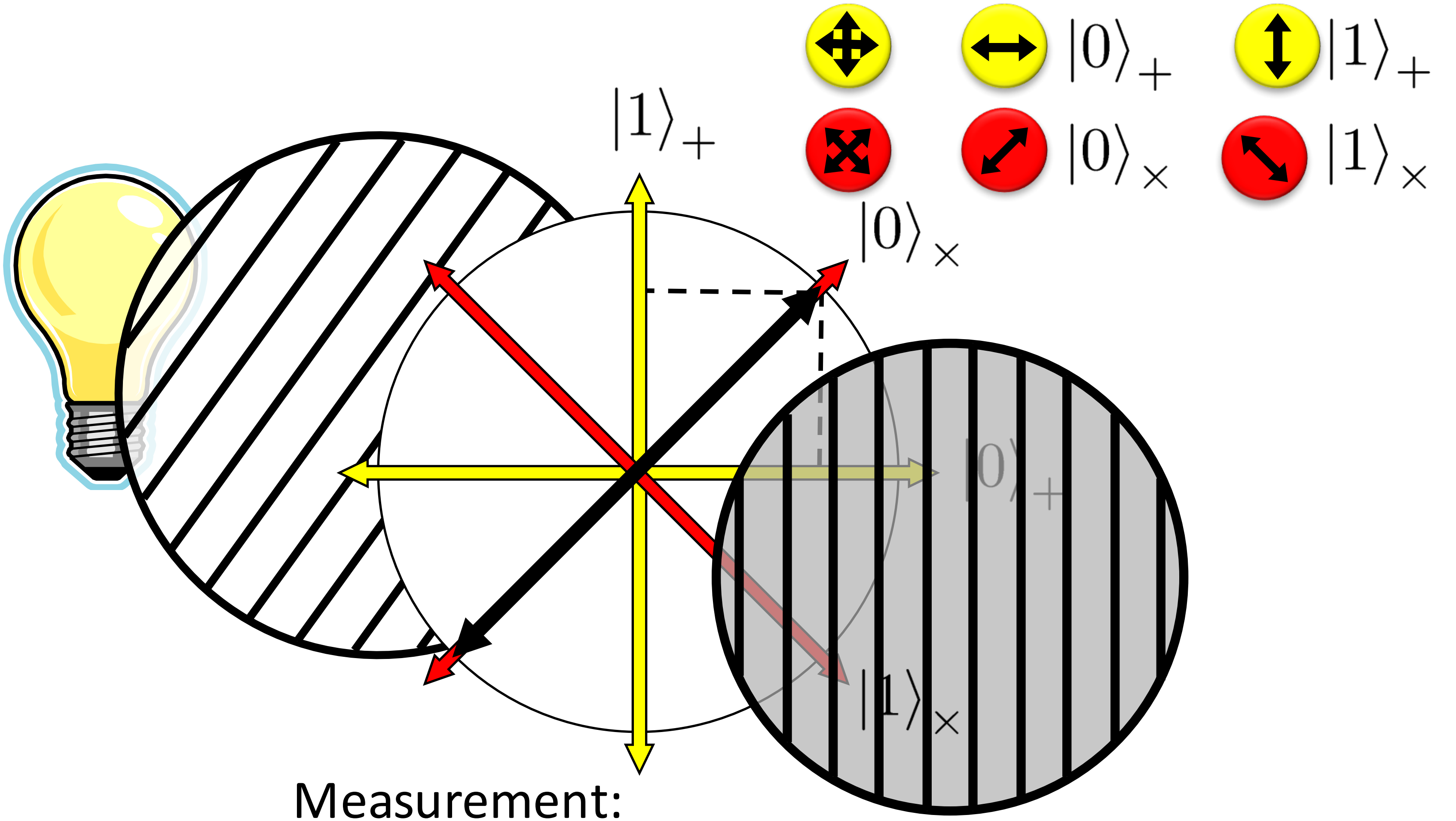
Measuring a Qubit



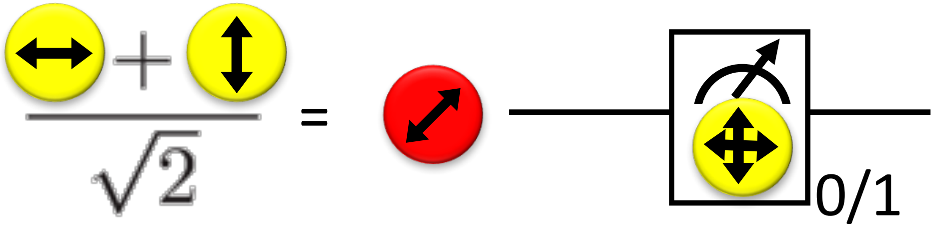
Measurement:

with prob. 1 yields 1

Diagonal/Hadamard Basis



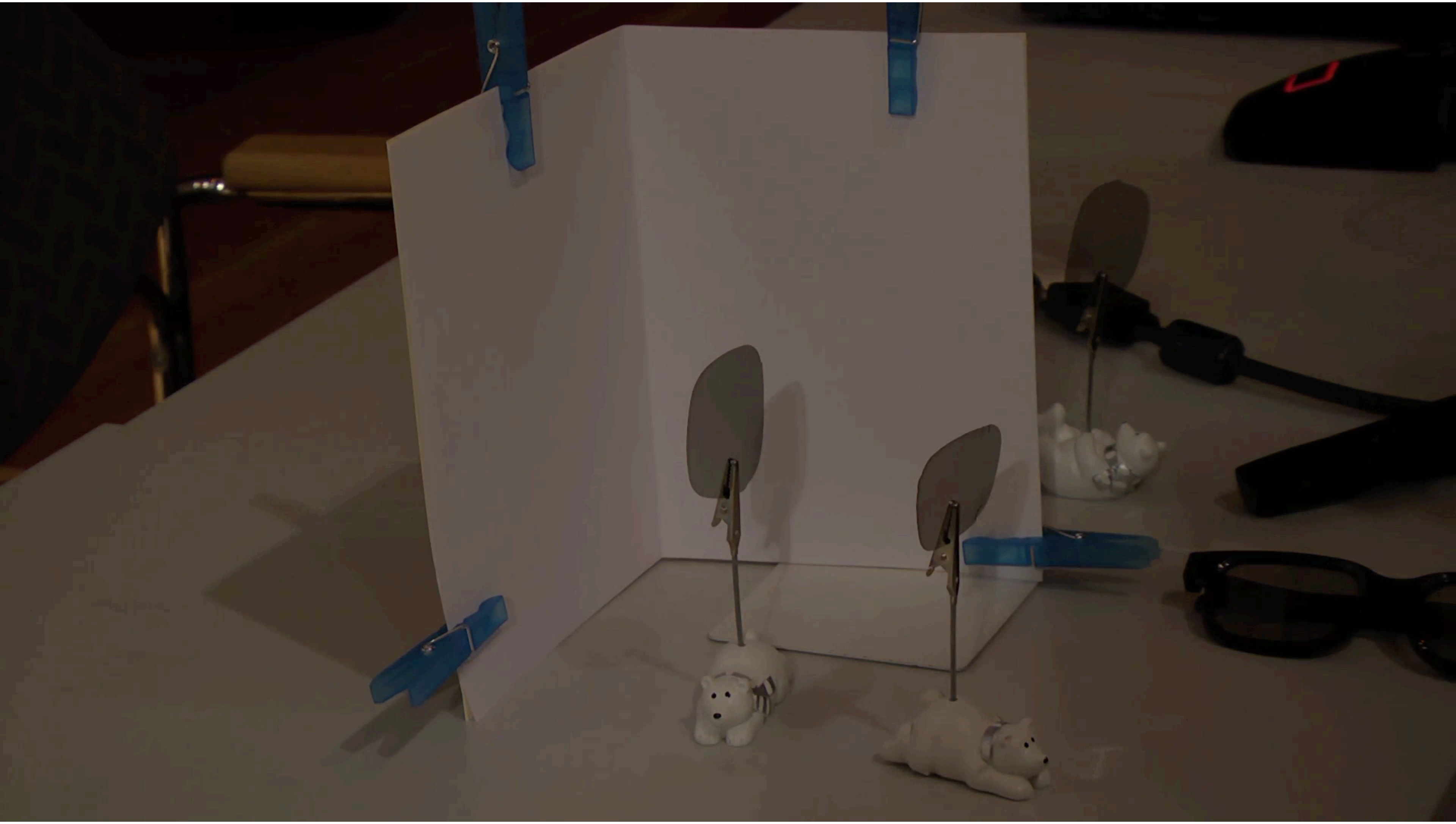
Measurement:



with prob. ½ yields 0 ↔

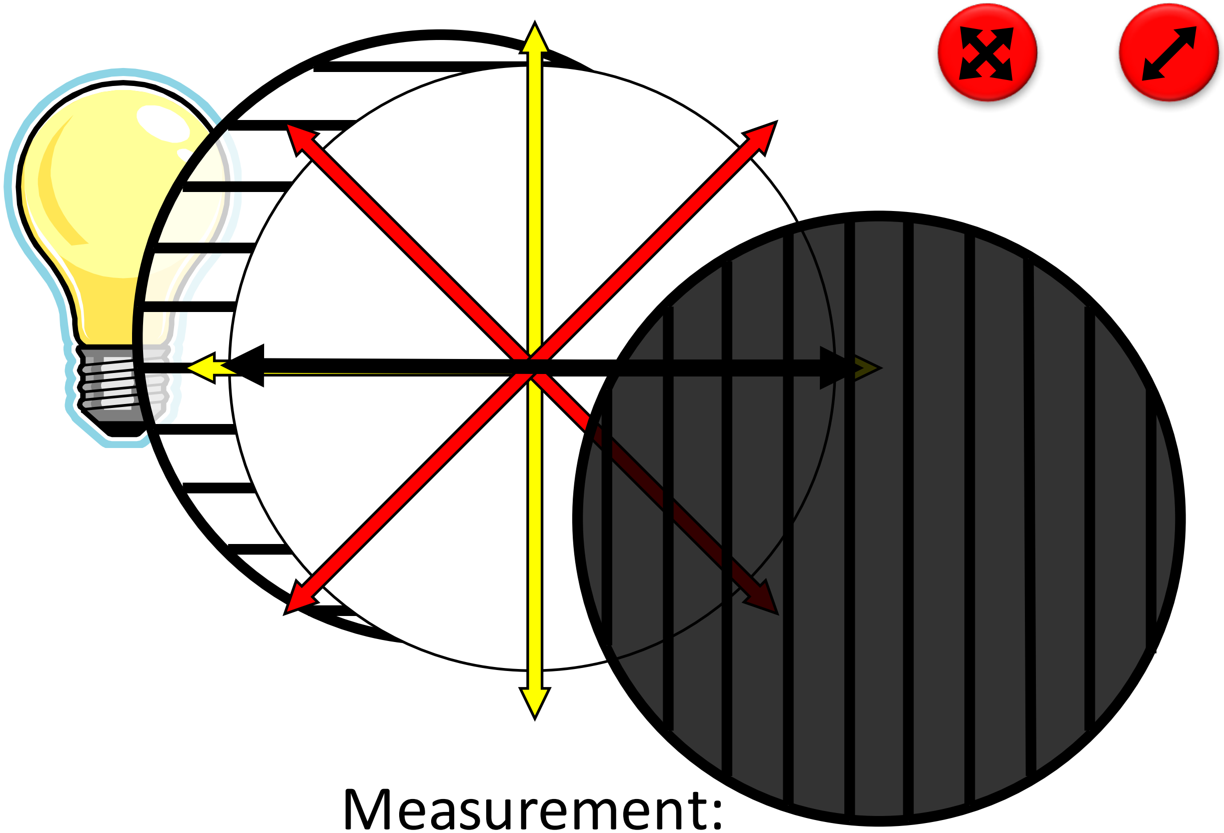
with prob. ½ yields 1 ↕

Video



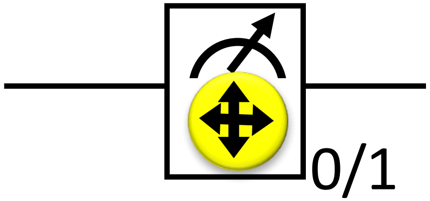
Measuring Collapses the State

✥	↔	$|0\rangle_+$	↕	$|1\rangle_+$
✖	⤢	$|0\rangle_\times$	⤡	$|1\rangle_\times$



Measurement:

$\frac{\leftrightarrow + \updownarrow}{\sqrt{2}} =$ ⤢

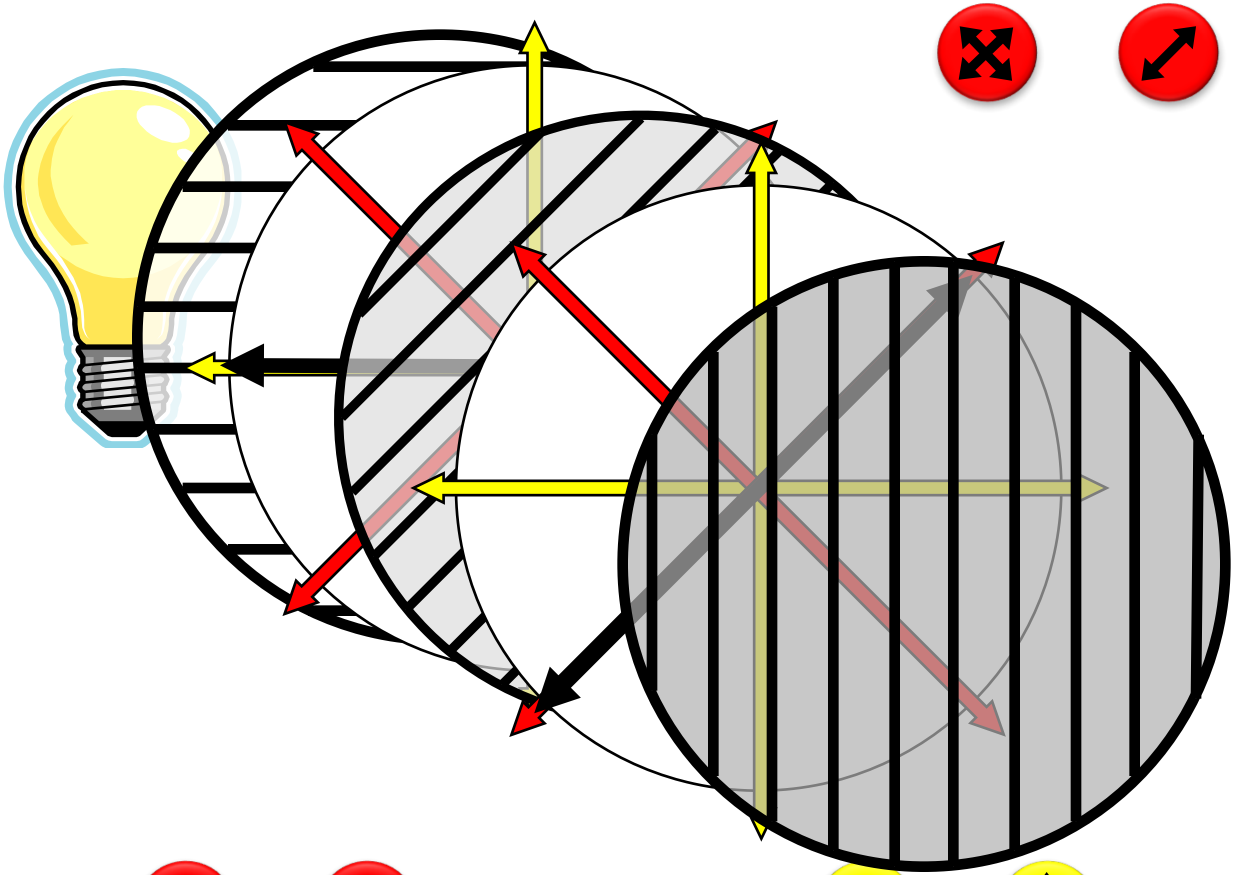


with prob. ½ yields 0 ↔

with prob. ½ yields 1 ↕

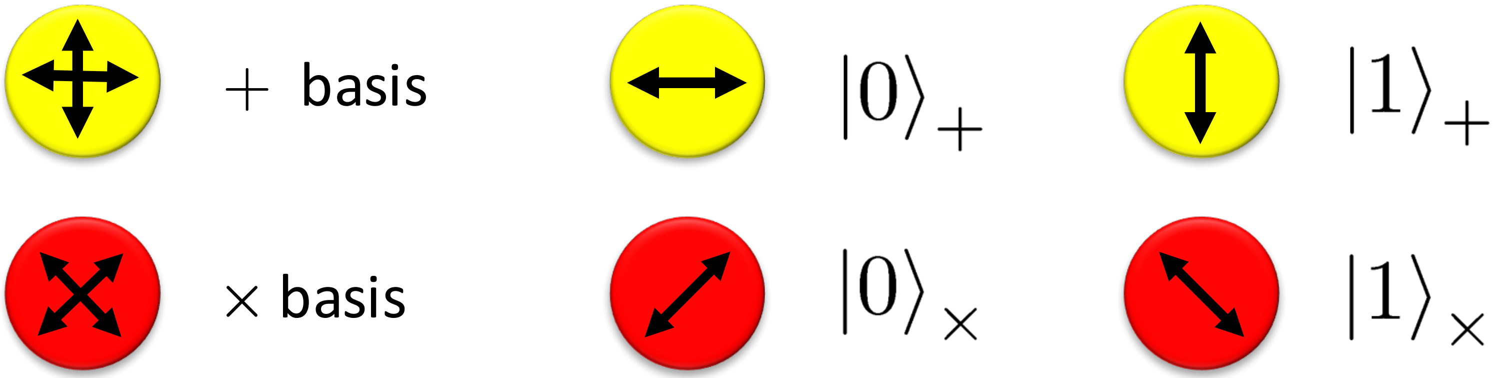
Measuring Collapses the State

✥	↔	$\vert 0\rangle_+$	↕	$\vert 1\rangle_+$
✕	⤢	$\vert 0\rangle_\times$	⤡	$\vert 1\rangle_\times$



$$\text{↔} = \frac{\text{⤢} + \text{⤡}}{\sqrt{2}} \rightarrow \text{⤢} = \frac{\text{↔} + \text{↕}}{\sqrt{2}} \rightarrow \text{↕}$$

Quantum Mechanics



$+$ basis

$|0\rangle_+$

$|1\rangle_+$

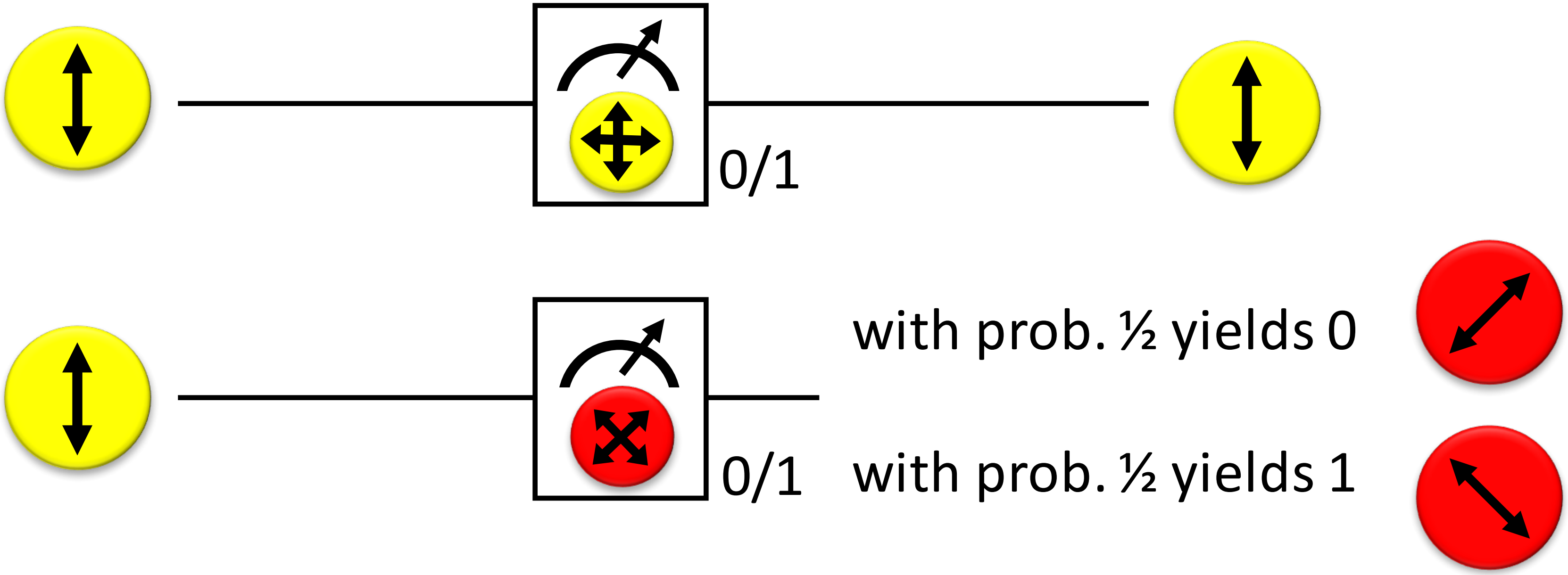
$\times$ basis

$|0\rangle_\times$

$|1\rangle_\times$

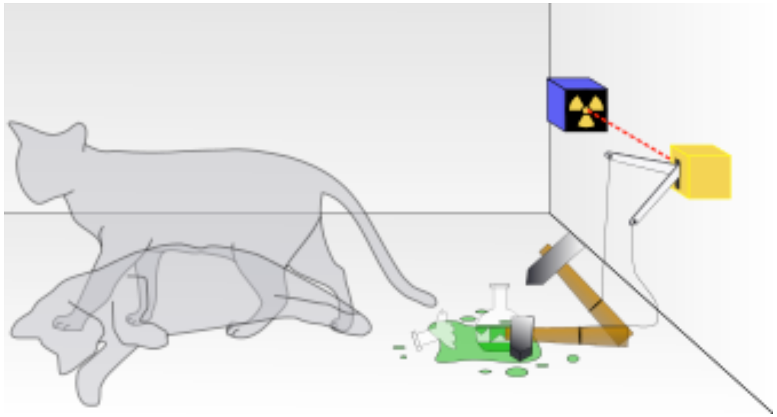
Measurements:

with prob. 1 yields 1

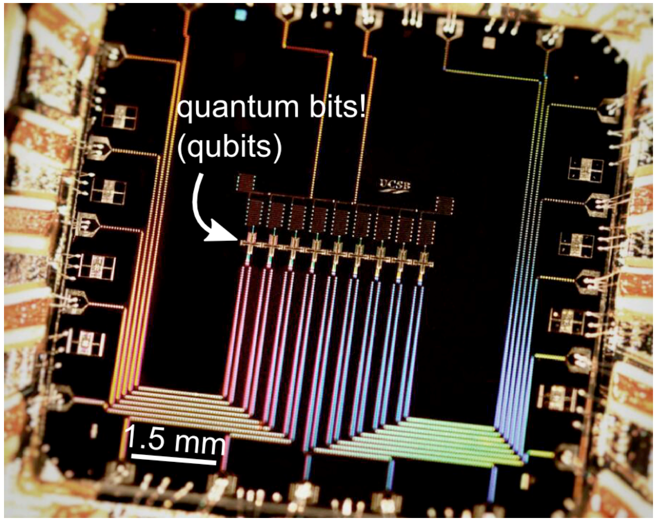


with prob. ½ yields 0

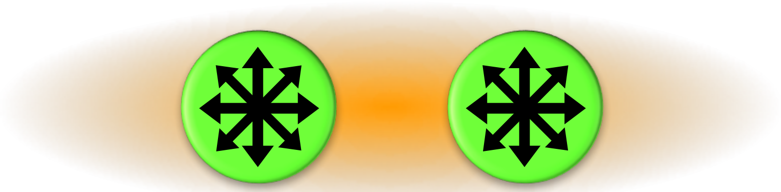
with prob. ½ yields 1



0

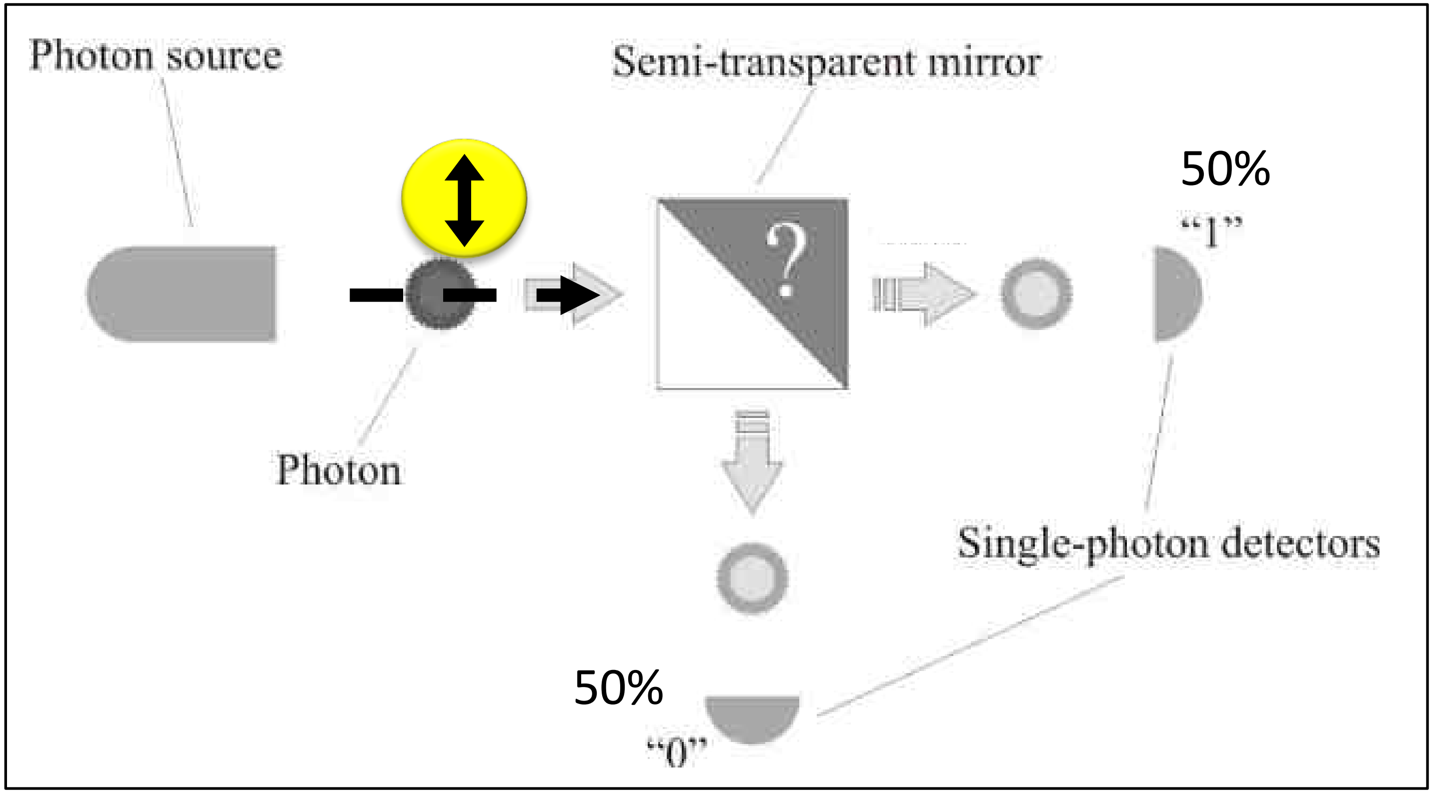


Wonderland of Quantum Mechanics



Demonstration of Quantum Technology

- generation of random numbers



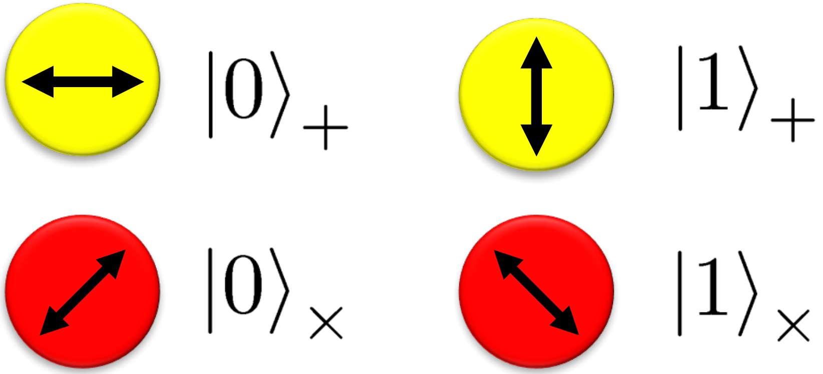
(diagram from idQuantique white paper)

- no quantum computation, only quantum communication required

What will you Learn from this Talk?

- ✓ Classical Cryptography
- ✓ Introduction to Quantum Mechanics
- Quantum Key Distribution
- Position-Based Cryptography

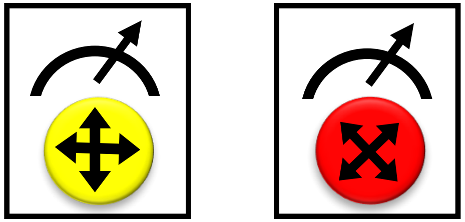
No-Cloning Theorem

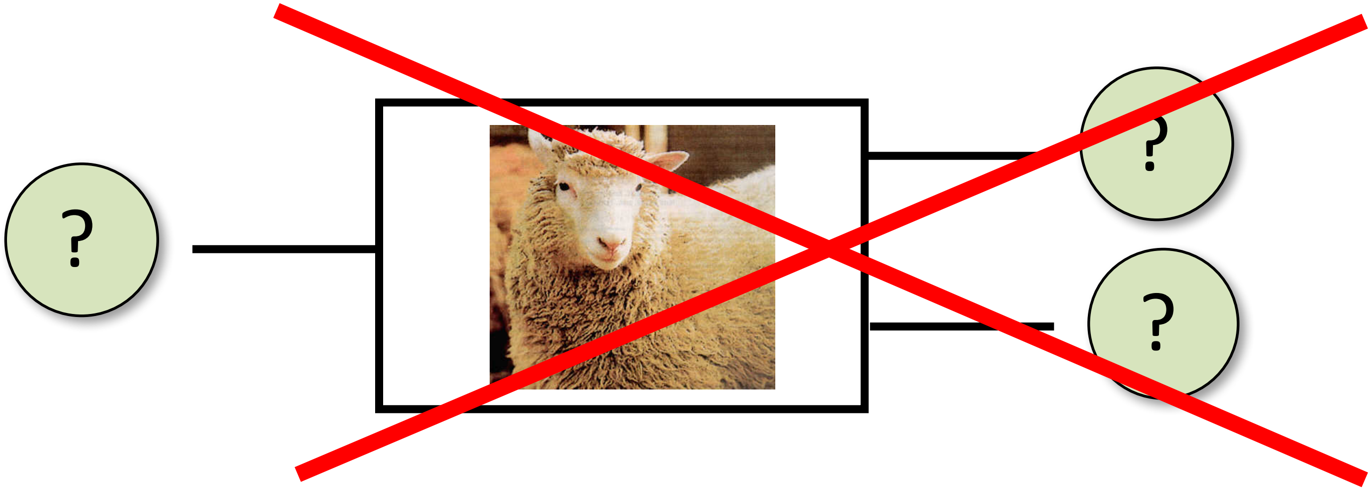


$|0\rangle_+$ $|1\rangle_+$

$|0\rangle_\times$ $|1\rangle_\times$

Quantum operations: $\boxed{U}$

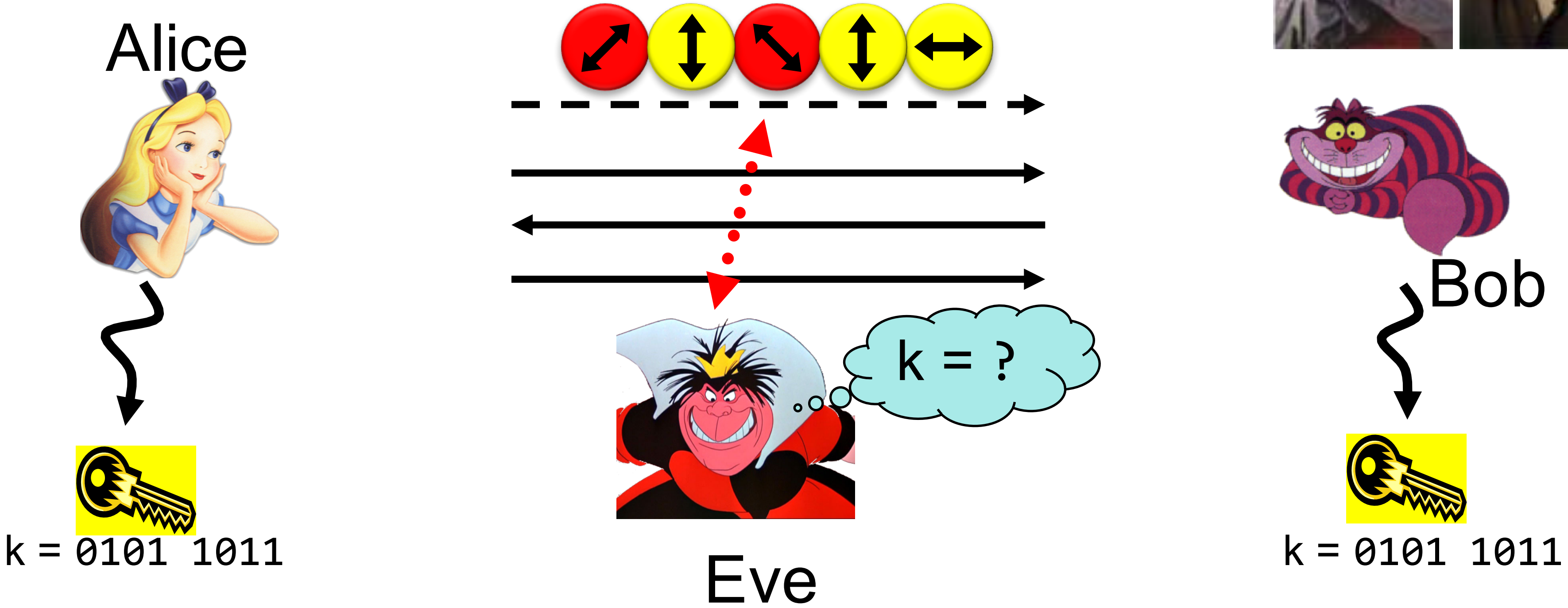




Proof: copying is a non-linear operation

Quantum Key Distribution (QKD)

[Bennett Brassard 84]



- Offers an quantum solution to the key-exchange problem which does not rely on computational assumptions (such as factoring, discrete logarithms, security of AES, SHA-3 etc.)
- Puts the players into the starting position to use symmetric-key cryptography (encryption, authentication etc.).

Quantum Cryptography Landscape

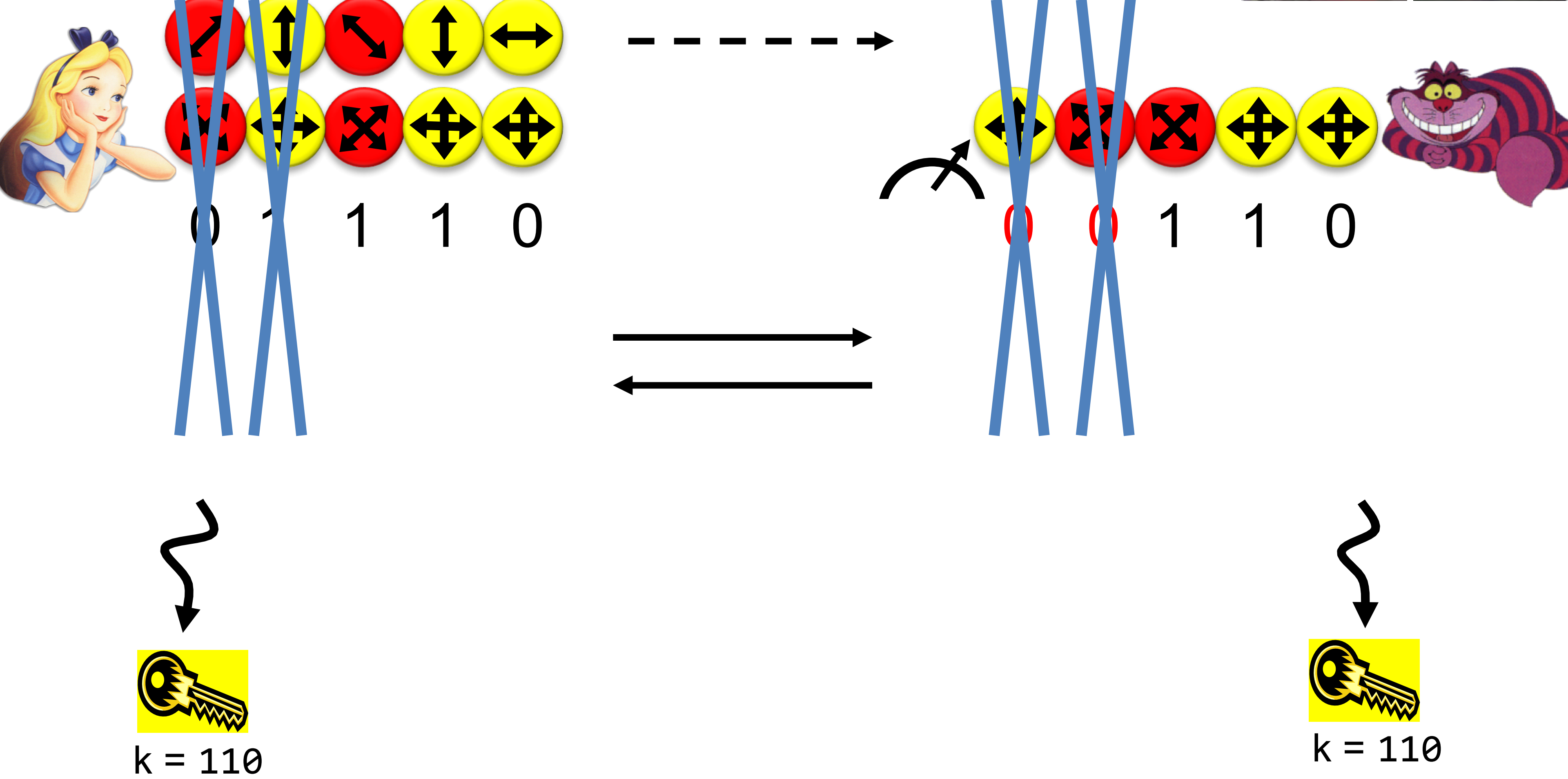
attackers systems	efficient classical attacks	efficient quantum attacks	everlasting security (store and break later)
AES	confident	longer keys	brute force
SHA	confident	longer outputs	brute force
RSA, DiscLogs	confident	Shor	brute force
Hash-Based Sign	probably	probably	brute force
McEliece	probably	probably	brute force
Lattice-based	probably	probably	brute force
QKD	🟩	🟩	🟩
physical security	🟩	🟩	🟩

technical difficulty (€)

Post Quantum Crypto

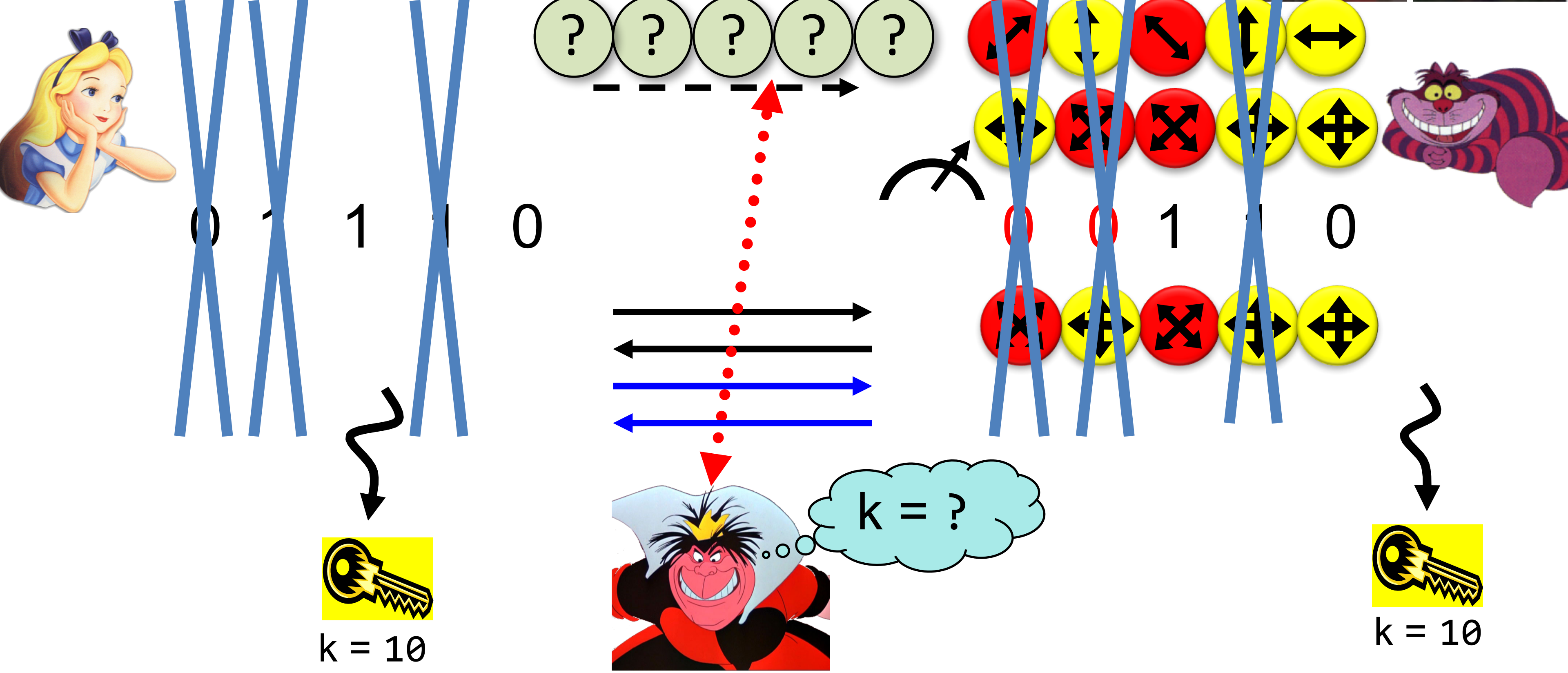
Quantum Key Distribution (QKD)

[Bennett Brassard 84]

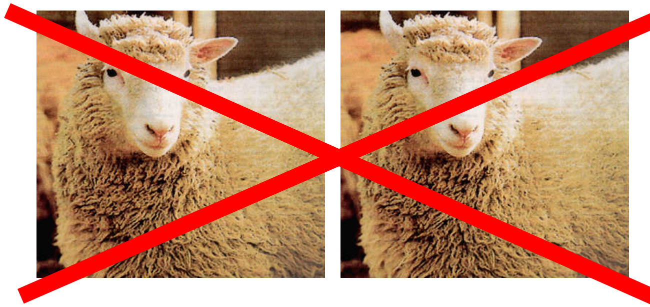


Quantum Key Distribution (QKD)

[Bennett Brassard 84]

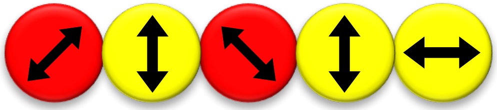


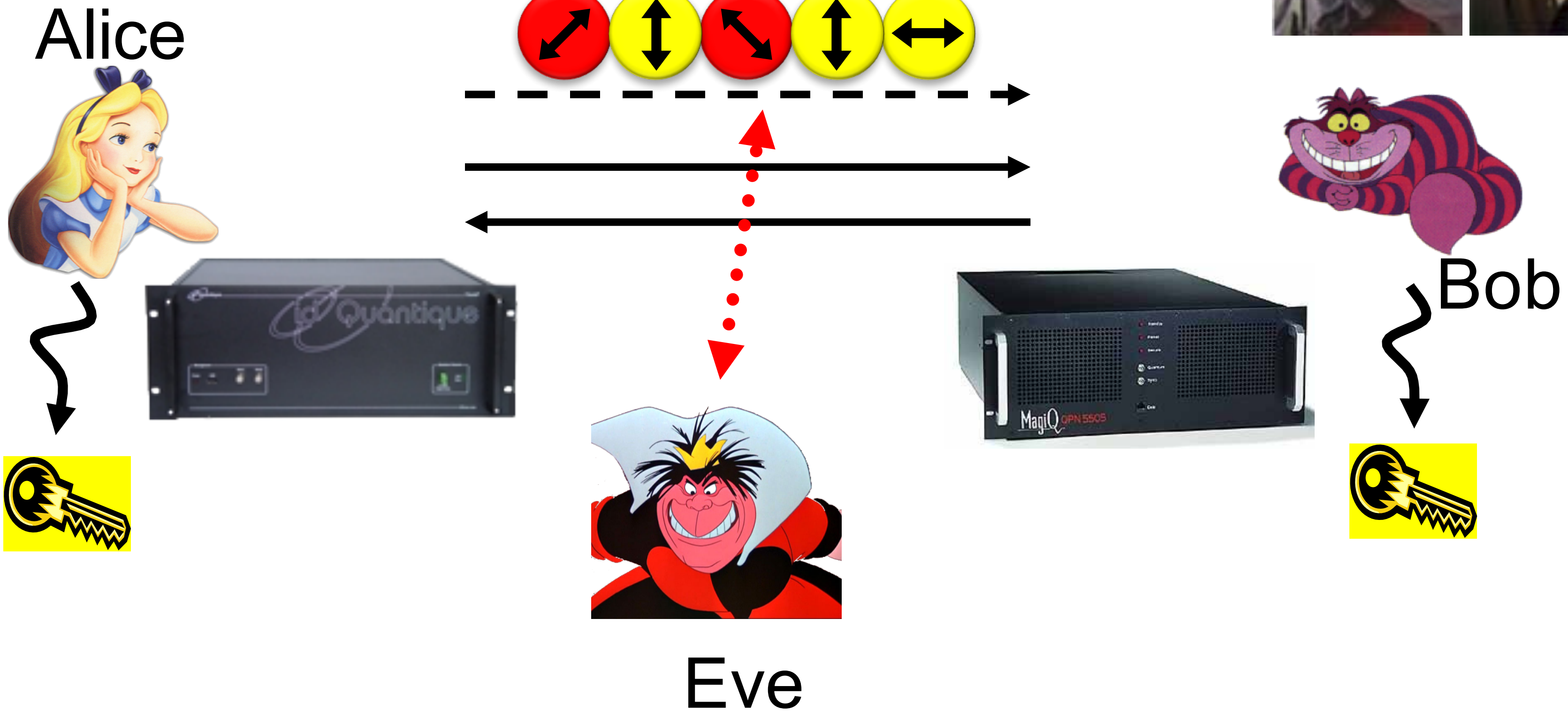
- Quantum states are unknown to Eve, she cannot copy them.
- Honest players can test whether Eve interfered.



Quantum Key Distribution (QKD)

[Bennett Brassard 84]



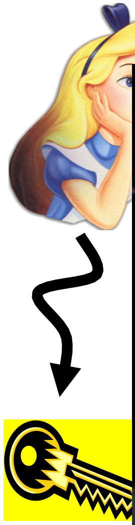


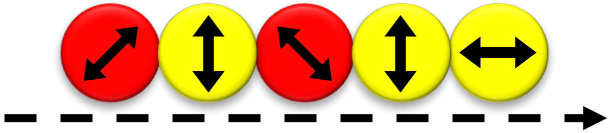
- technically feasible: no quantum computer required, only quantum communication

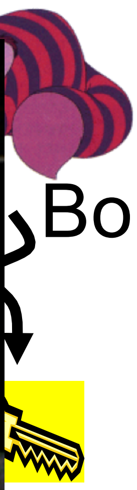
Quantum Key Distribution (QKD)

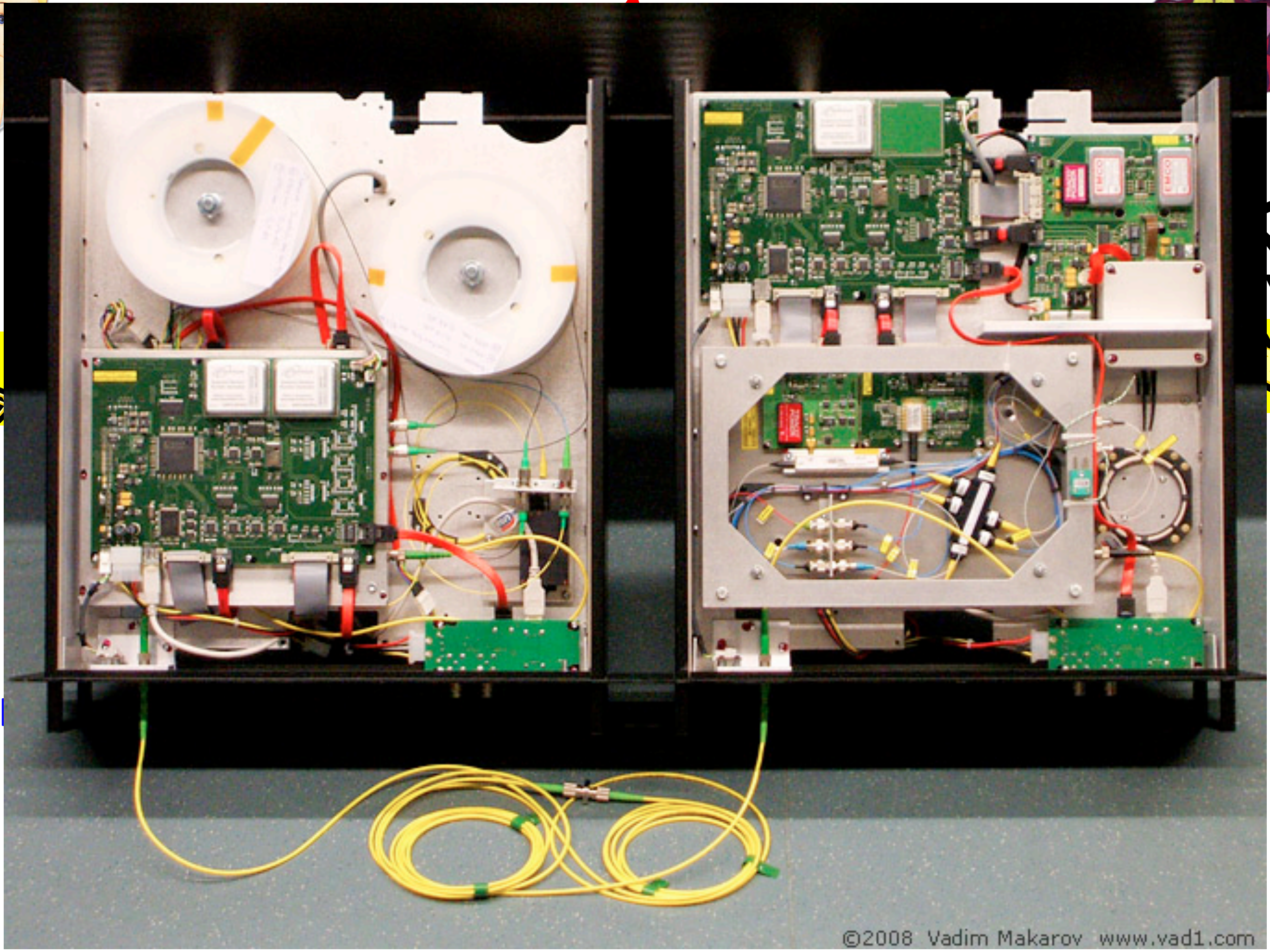
[Bennett Brassard 84]

Alice







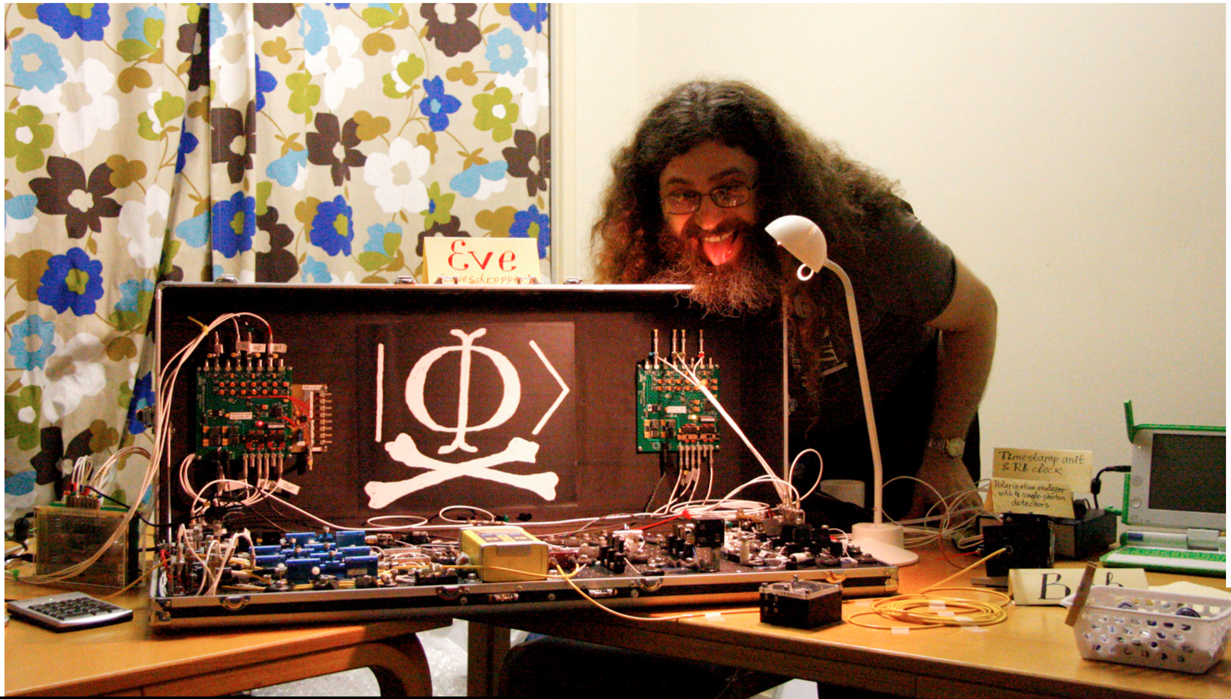


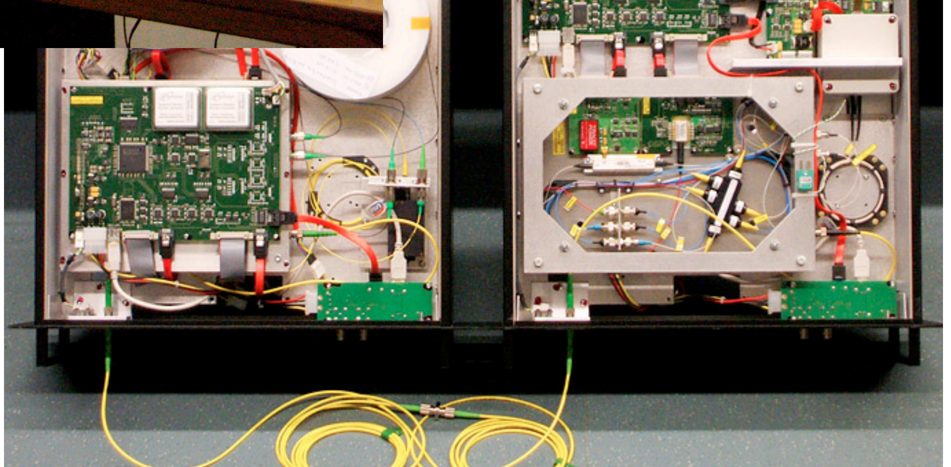
©2008 Vadim Makarov www.vad1.com

- tech
  only

Quantum Hacking

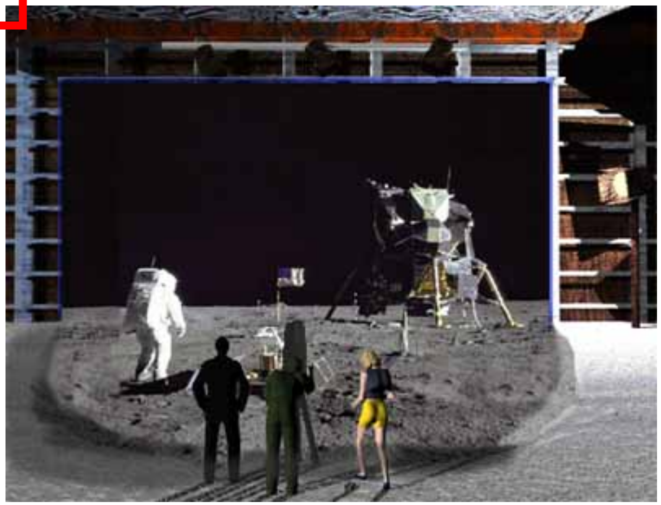
e.g. by the group of Vadim Makarov (University of Waterloo, Canada)


Eve
eavesdropper
Timestamp unit & Rb clock
Polarization analyzer with 4 single-photon detectors
Bob



What will you Learn from this Talk?

- ✓ Classical Cryptography
- ✓ Introduction to Quantum Mechanics
- ✓ Quantum Key Distribution
- Position-Based Cryptography



Position-Based Cryptography

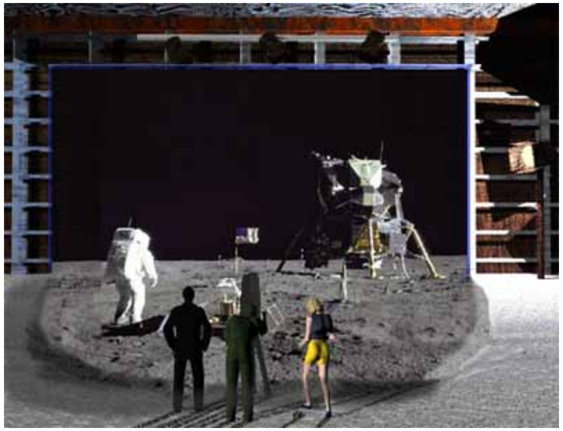
- Typically, cryptographic players use credentials such as
  - secret information (e.g. password or secret key)
  - authenticated information
  - biometric features

Can the geographical location of a player be used as cryptographic credential ?

Position-Based Cryptography

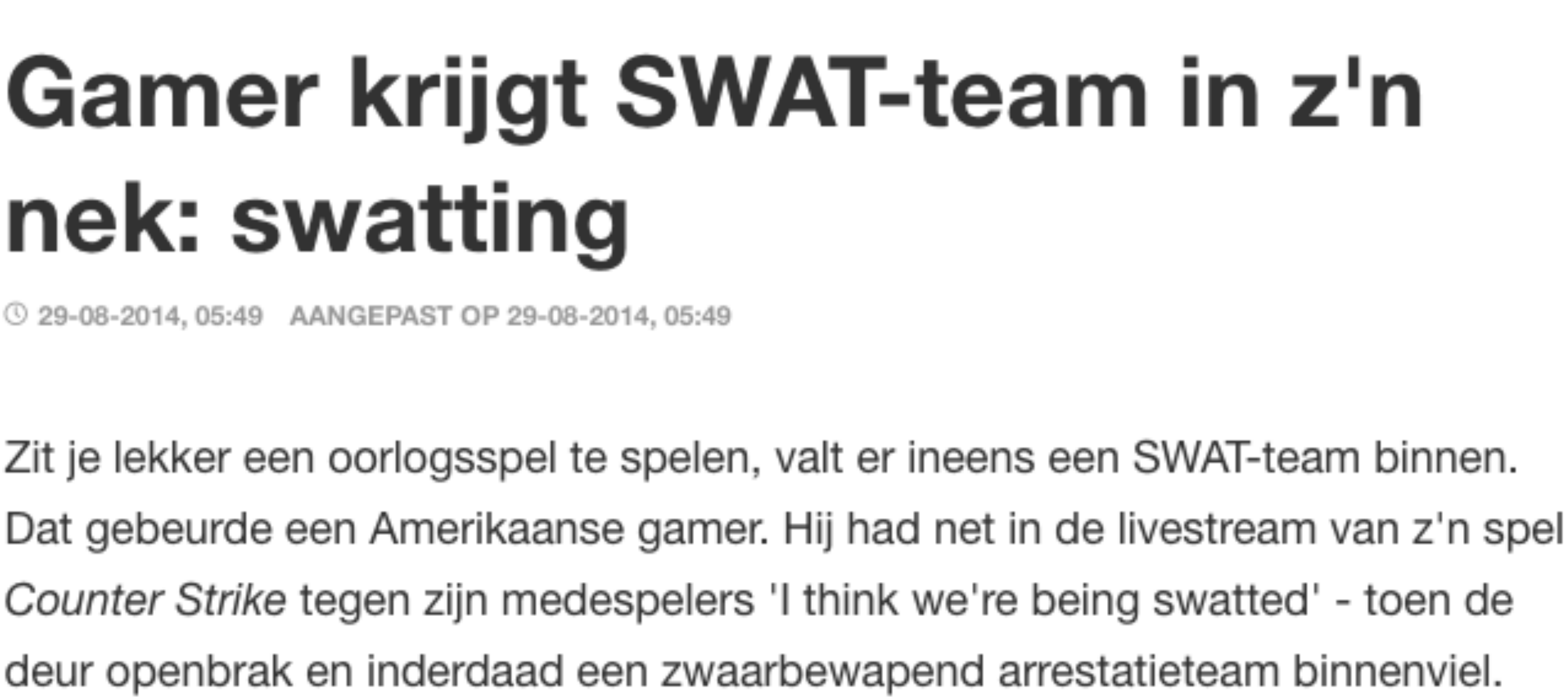
Can the geographical location of a player be used as sole cryptographic credential ?

- Possible Applications:
  - Launching-missile command comes from within your military headquarters
  - Talking to the correct assembly
  - Pizza-delivery problem / avoid fake calls to emergency services
  - …



Position-Based Cryptography

NOS OP 3



Gamer krijgt SWAT-team in z'n nek: swatting

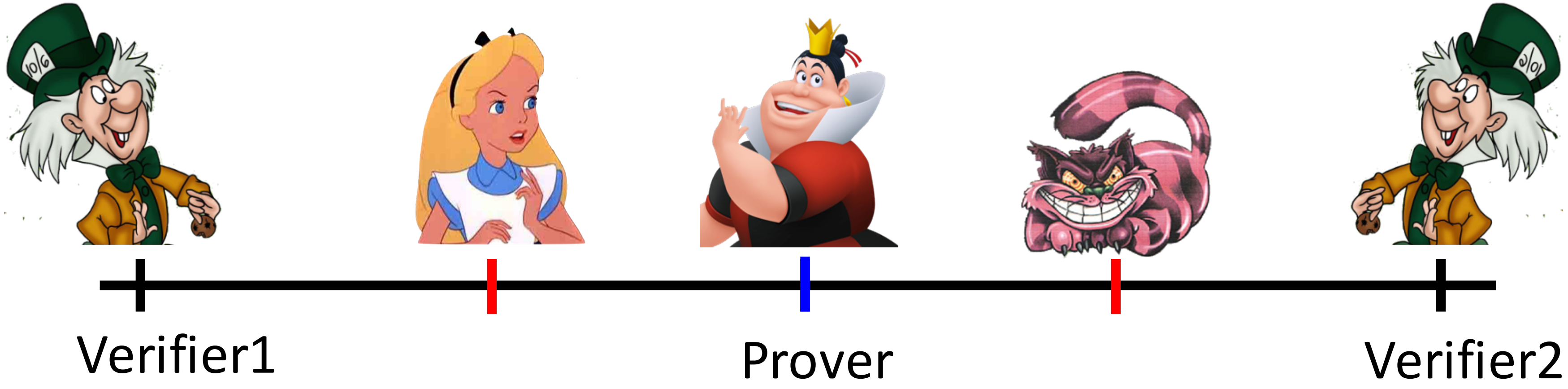
🕓 29-08-2014, 05:49 AANGEPAST OP 29-08-2014, 05:49

Zit je lekker een oorlogsspel te spelen, valt er ineens een SWAT-team binnen. Dat gebeurde een Amerikaanse gamer. Hij had net in de livestream van z'n spel *Counter Strike* tegen zijn medespelers 'I think we're being swatted' - toen de deur openbrak en inderdaad een zwaarbewapend arrestatieteam binnenviel.

Dat was allemaal live te zien op de webcam:

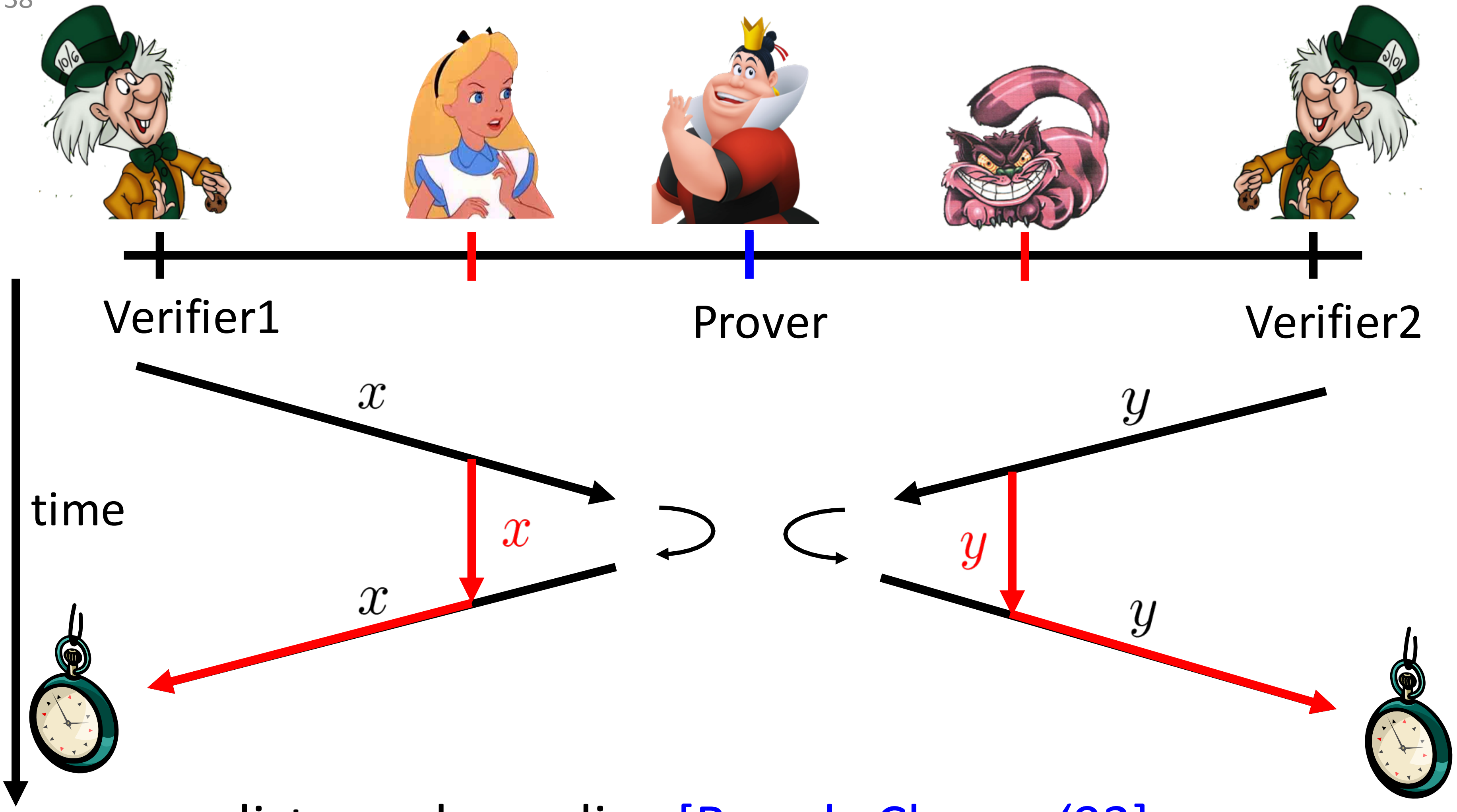
https://youtu.be/TiW-BVPCbZk?t=117

Basic task: Position Verification



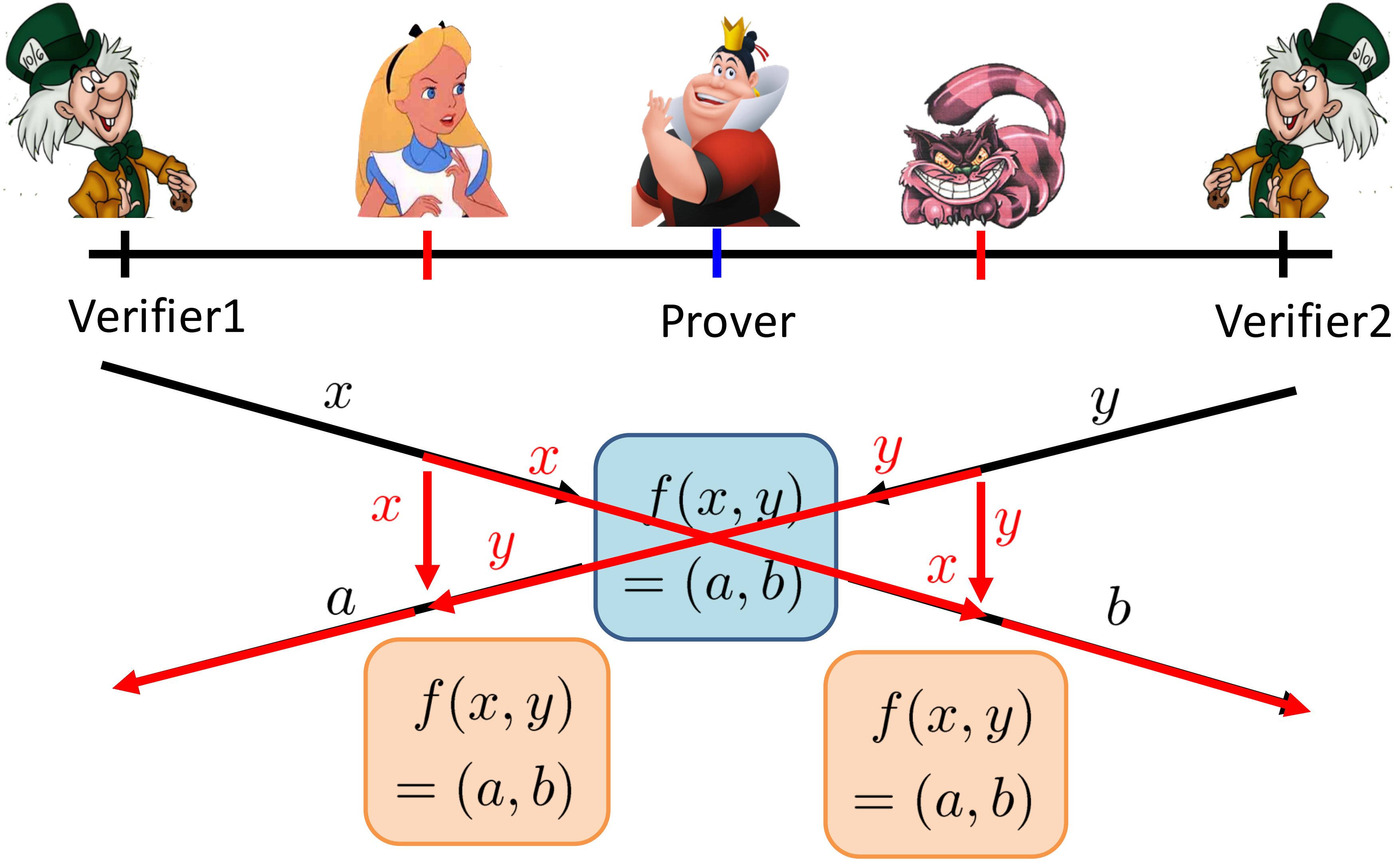
- Prover wants to convince verifiers that she is at a particular position
- no coalition of (fake) provers, i.e. not at the claimed position, can convince verifiers
- (over)simplifying assumptions:
  - communication at speed of light
  - instantaneous computation
  - verifiers can coordinate

Position Verification: First Try



- distance bounding [Brands Chaum '93]

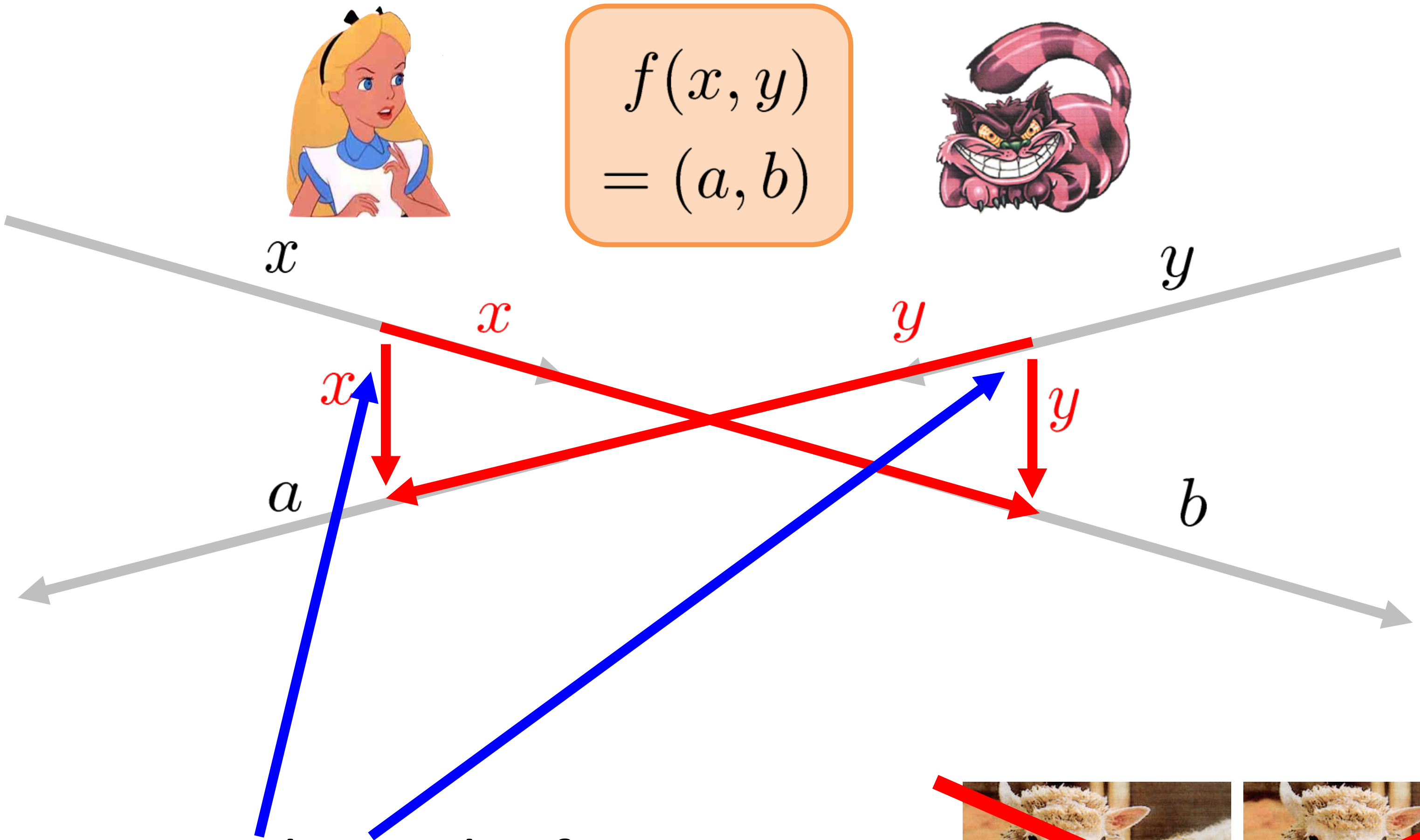
Position Verification: Second Try



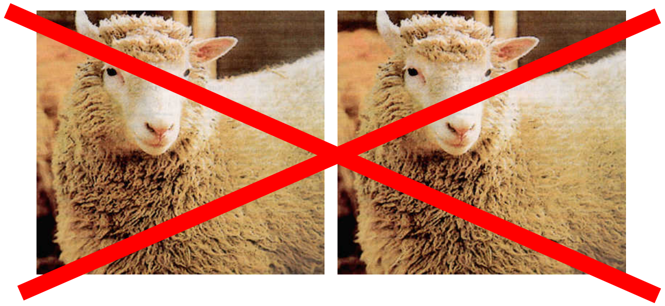
position verification is classically impossible !

[Chandran Goyal Moriarty Ostrovsky 09]

The Attack

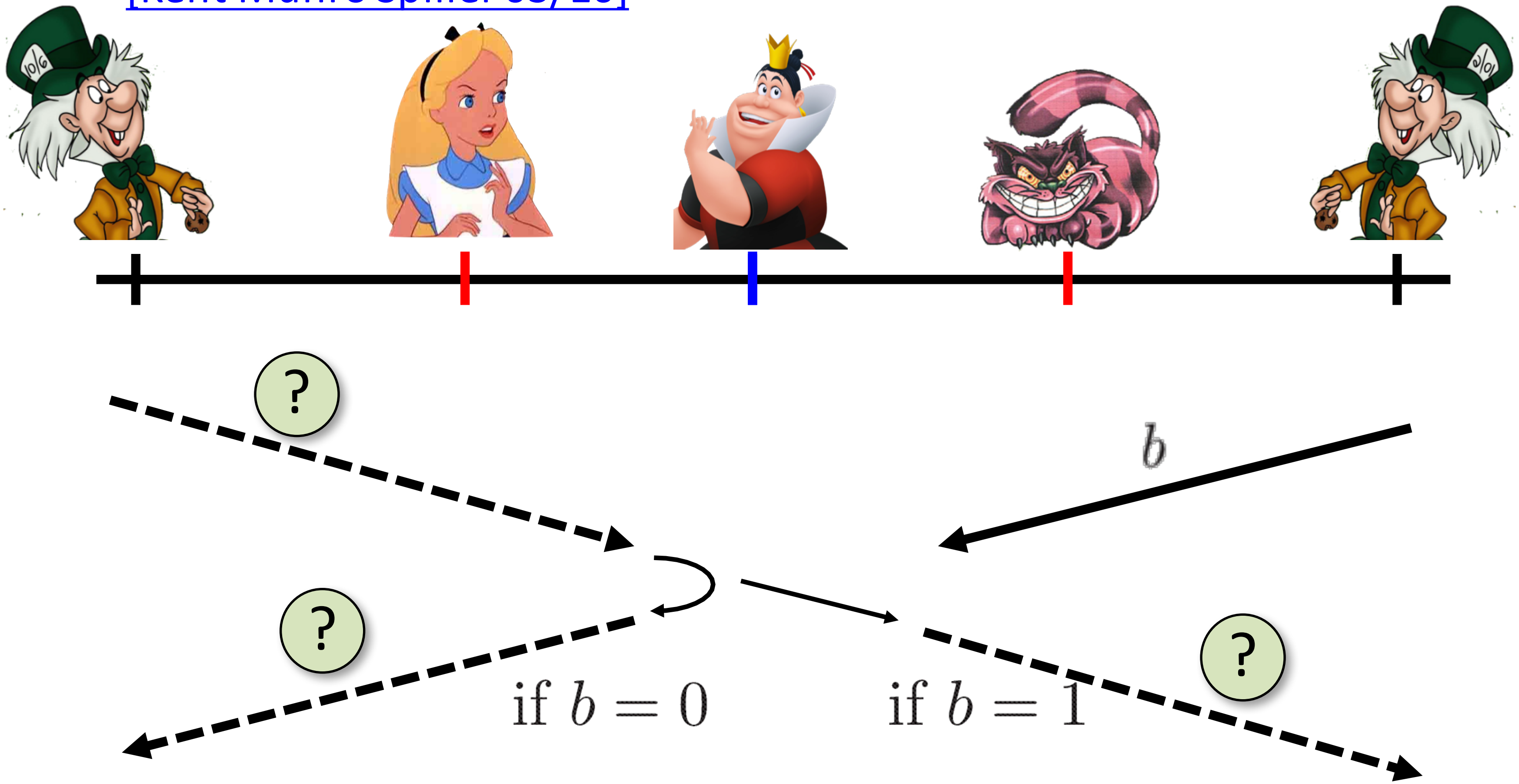


- copying classical information
- this is impossible quantumly



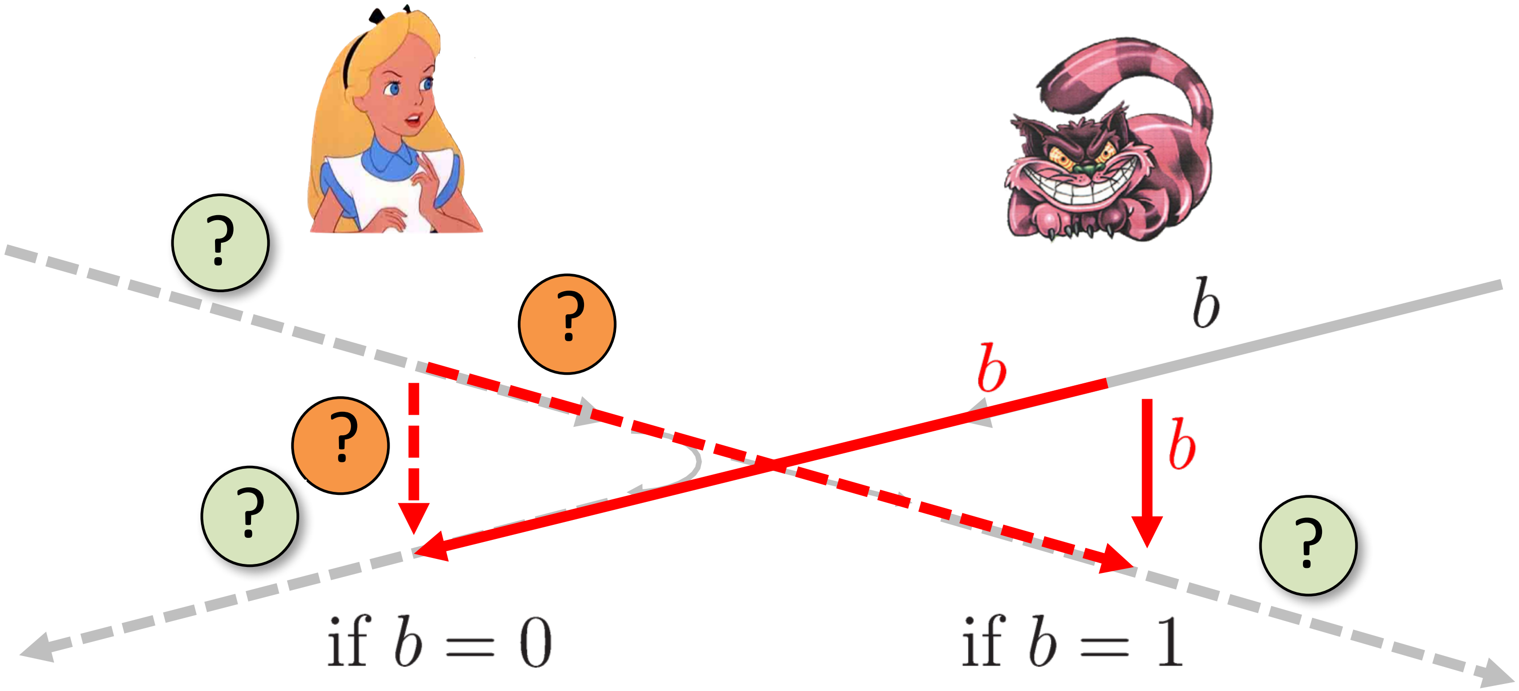
Position Verification: Quantum Try

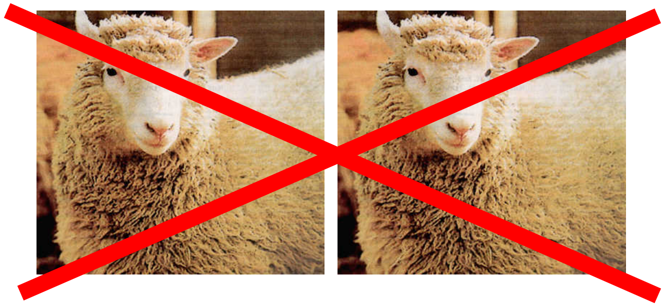
[Kent Munro Spiller 03/10]



- Can we brake the scheme now?

Attacking Game

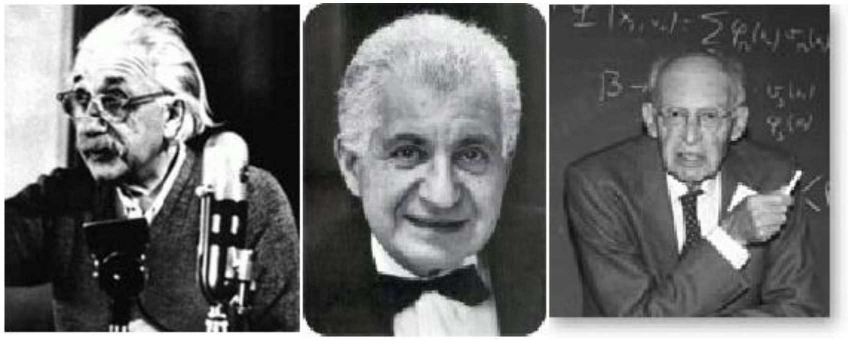


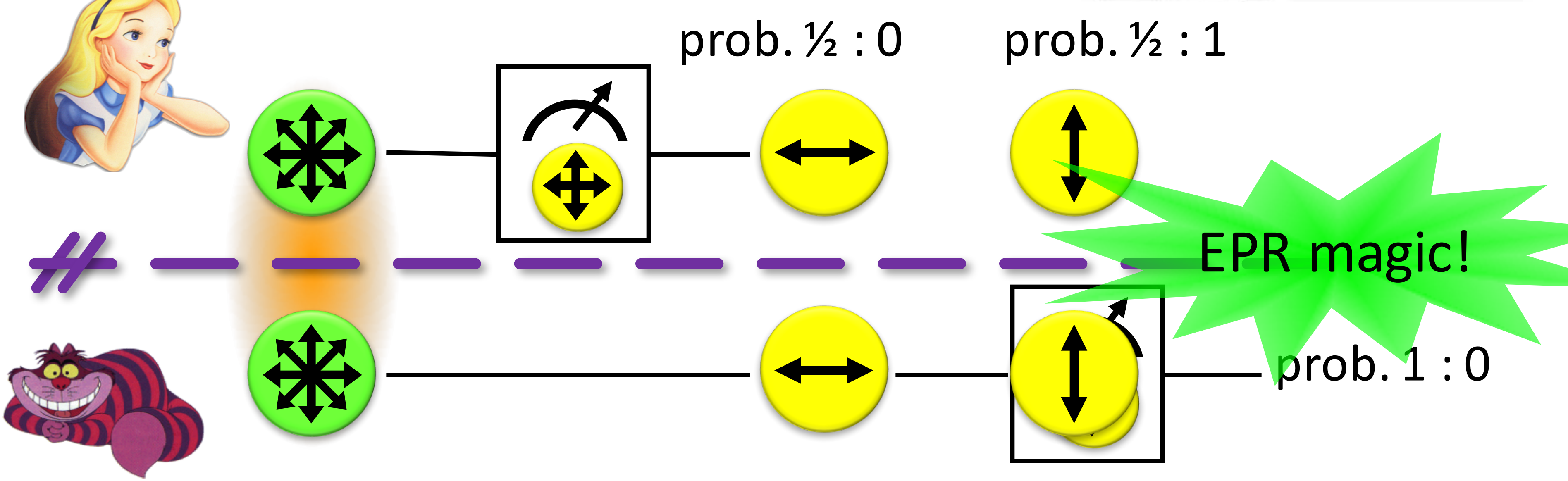


- Impossible to cheat due to no-cloning theorem
- Or not?

EPR Pairs

[Einstein Podolsky Rosen 1935]

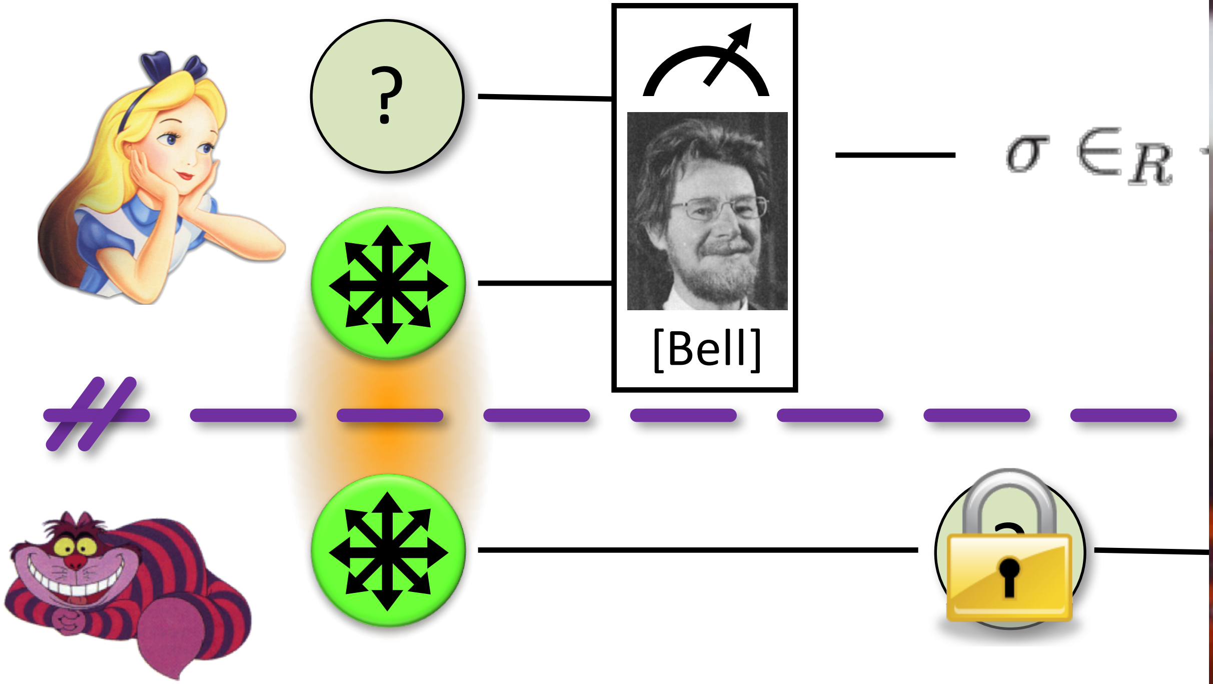




- “spukhafte Fernwirkung” (spooky action at a distance)
- EPR pairs do not allow to communicate (no contradiction to relativity theory)
- can provide a shared random bit

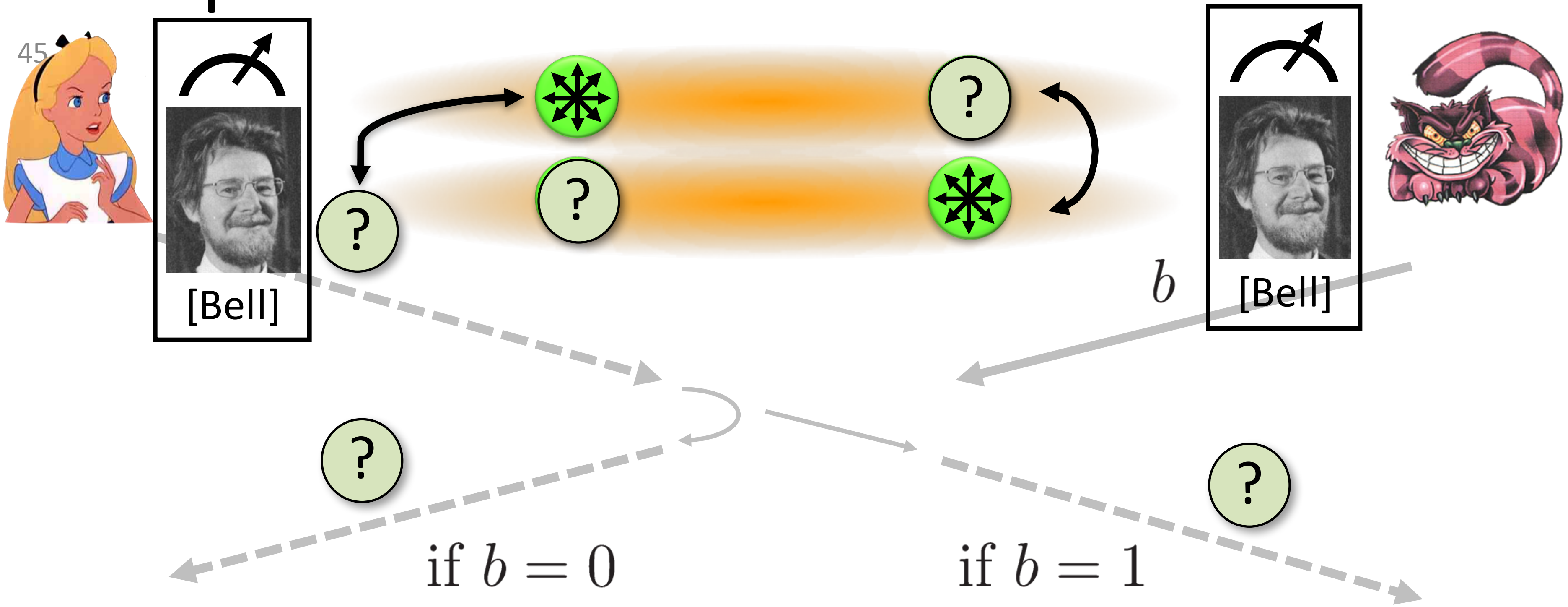
Quantum Teleportation

[Bennett Brassard Crépeau Jozsa Peres Wootters 19



- does not contradict relativity theory
- Bob can only recover the teleported qubit after receiving the classical information σ

Teleportation Attack



- It is possible to cheat with entanglement !!
- Quantum teleportation allows to break the protocol perfectly.

No-Go Theorem

[Buhrman, Chandran, Fehr, Gelles, Goyal, Ostrovsky, Schaffner 2010] [Beigi Koenig 2011]

- Any position-verification protocol can be broken using an exponential number of entangled qubits.

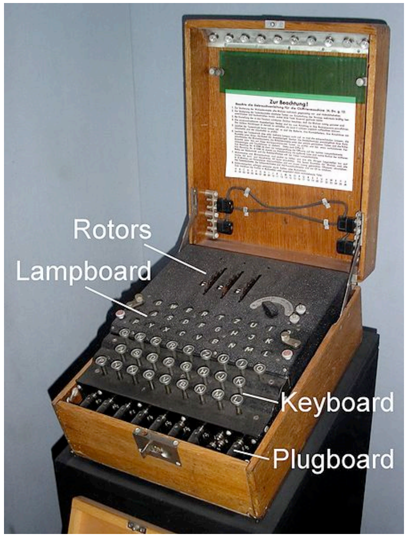
- Question: Are so many quantum resources really necessary?

- Does there exist a protocol such that:
  - honest prover and verifiers are efficient, but
  - any attack requires lots of entanglement

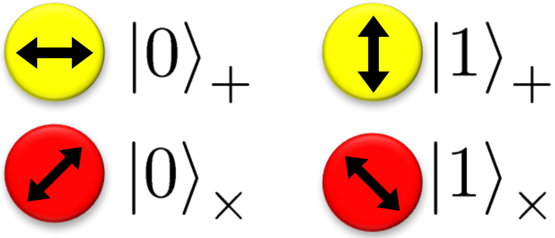
see http://homepages.cwi.nl/~schaffne/positionbasedqcrypto.php for recent developments

What Have You Learned from this Talk?

✓ Classical Cryptography

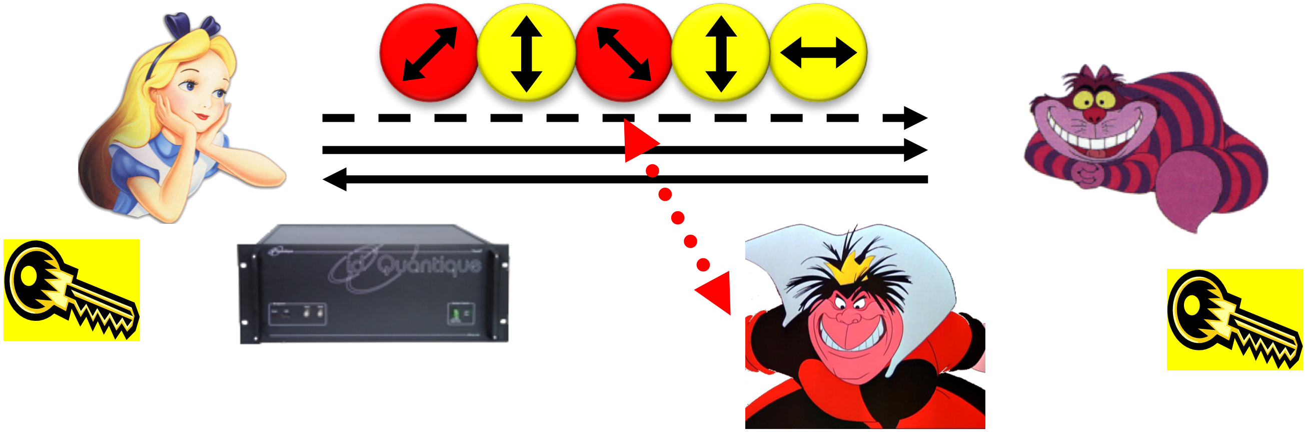


✓ Quantum Computing & Teleportation

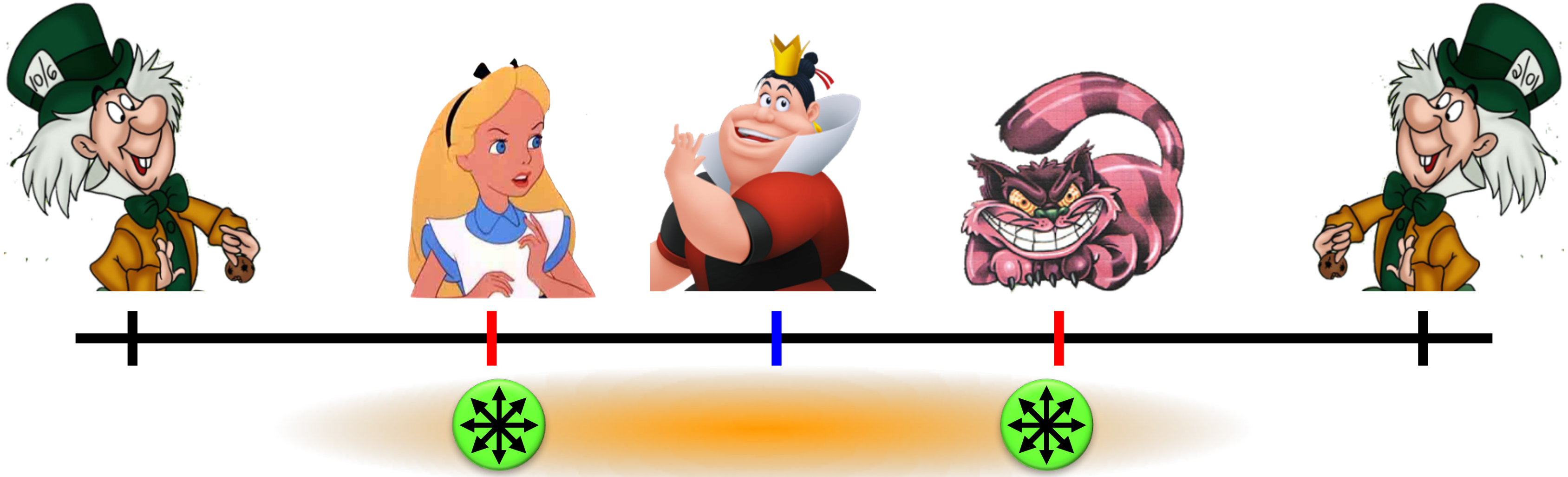


What Have You Learned from this Talk?

✓ Quantum Key Distribution (QKD)



✓ Position-Based Cryptography



Thank you for your attention!

Questions

QuSoft

CWI

NWO
Nederlandse Organisatie voor
Wetenschappelijk Onderzoek