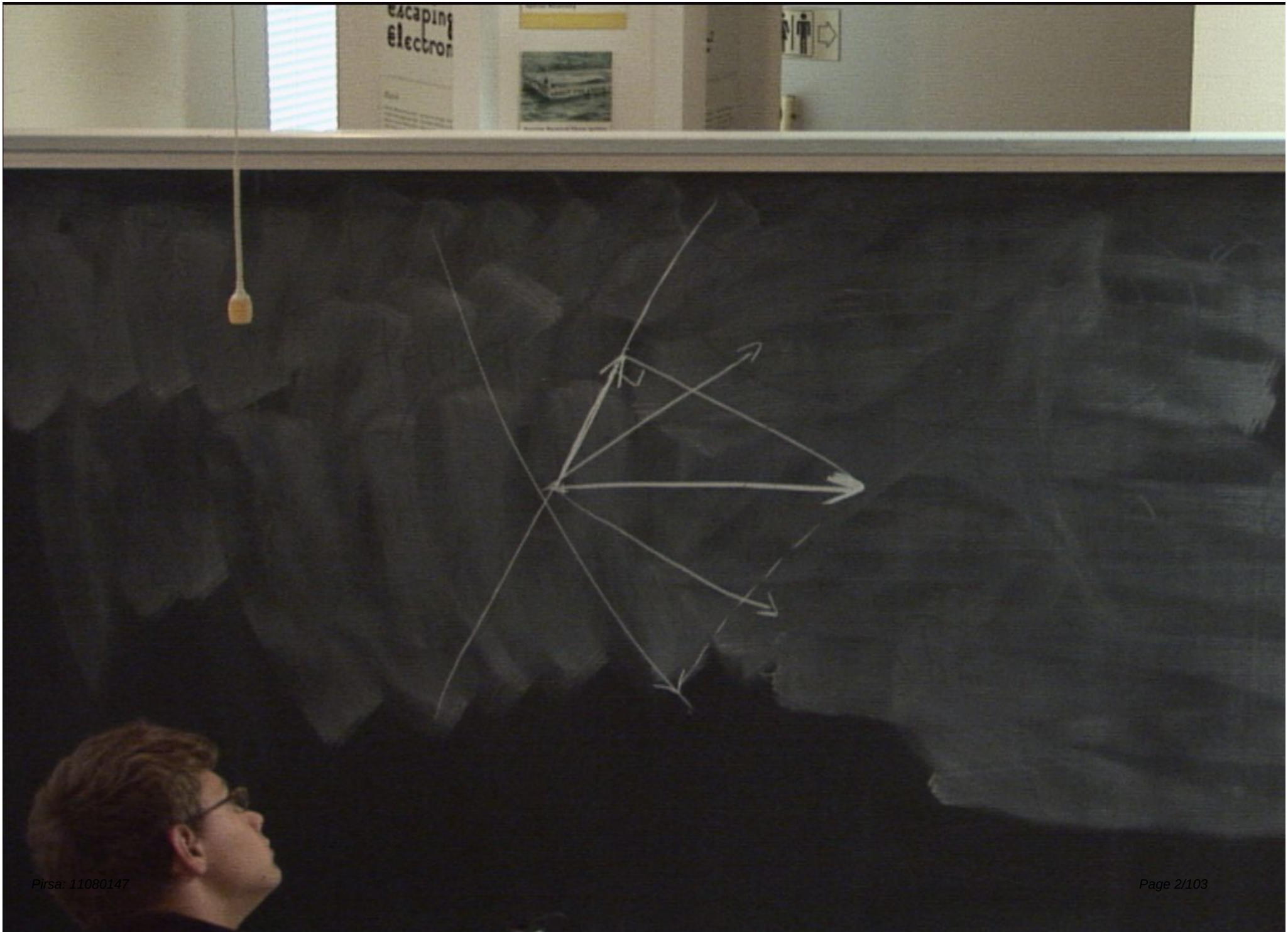
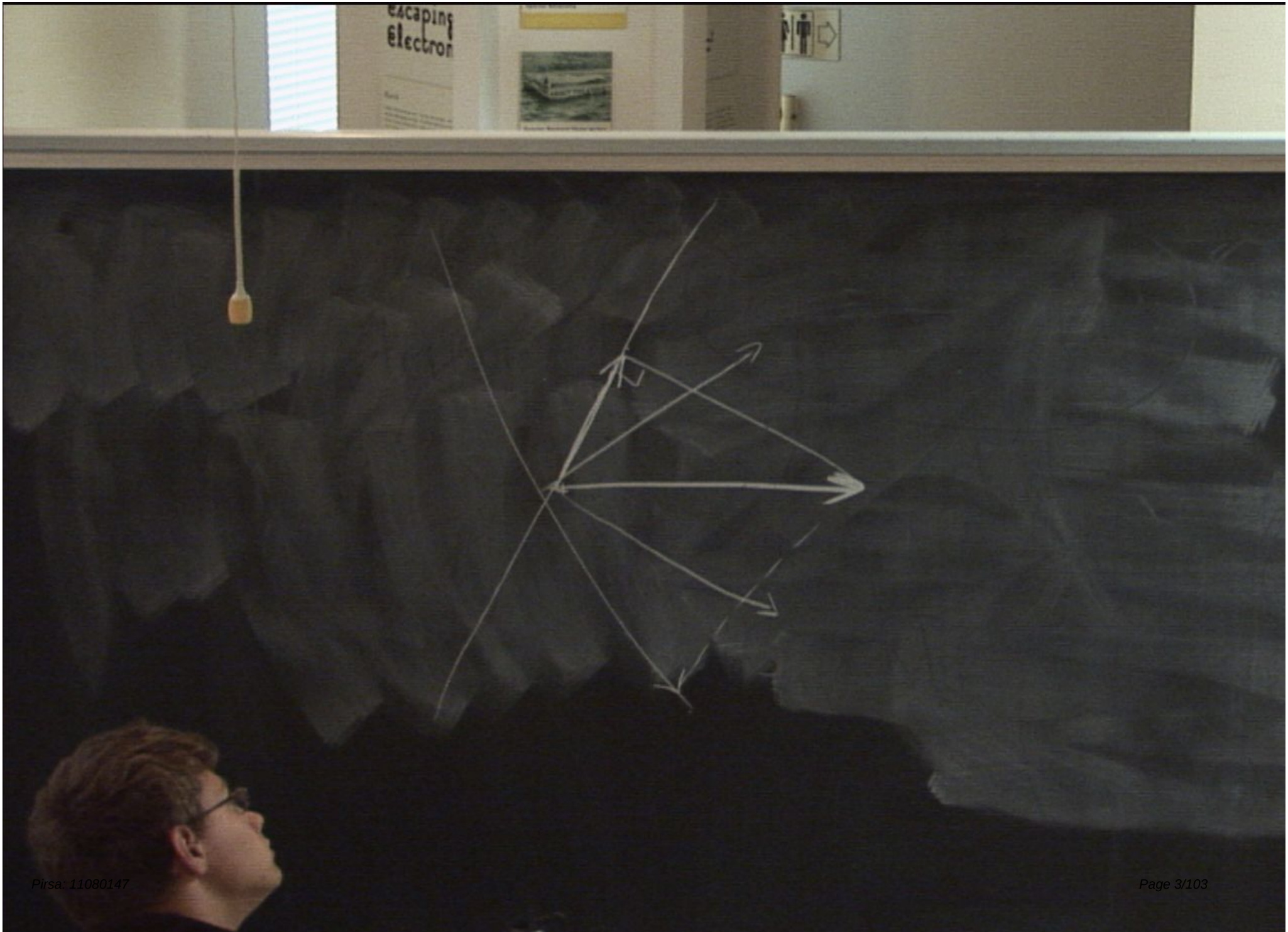
Title: ISSYP 2011 - Quantum Cryptograpy

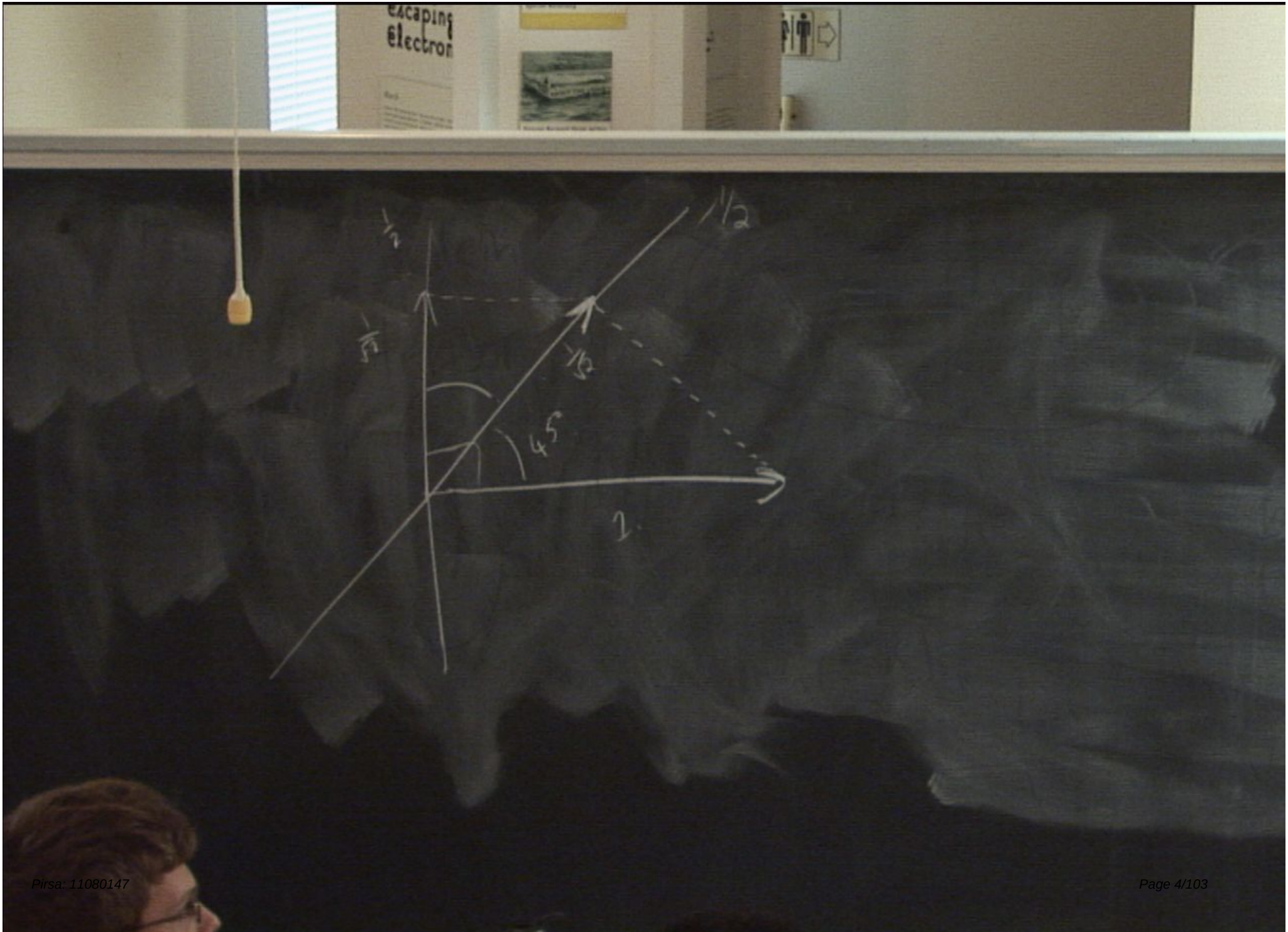
Date: Aug 03, 2011 10:30 AM

URL: http://pirsa.org/11080147

Abstract: This is an introductory talk on quantum cryptography, focusing on quantum key distribution (QKD) with a cool little demo involving polarized light. QKD gives us the amazing ability to send messages with absolute security


escaping
electron


Escaping
Electron


escaping
electron
1/2
1/2
1/√2
1/√2
45
1.

Polarization of light

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- Diagonal = horizontal + vertical

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- Horizontal component of light passes through; Vertically polarized component is blocked

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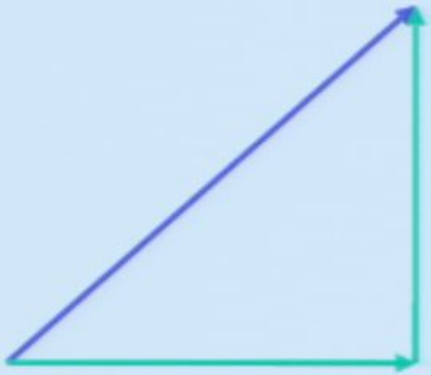

- Horizontal component of light passes through; Vertically polarized component is blocked
- Not a bulk phenomenon

Spot the difference?

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- Which photo was taken with a polarizing filter?

Spot the difference?

- Which photo was taken with a polarizing filter?
- Light reflected from the windows is polarized
- The filter absorbs the polarized light

Encryption

- Alice wants to send a note to Bob across the room
- Passes it to a neighbour, to be passed on to Bob
- How can she keep the others from reading the contents?

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- Earliest recorded method known
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the quick brown fox jumps over the lazy dog
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```

- Example

```
the quick brown fox jumps over the lazy dog
WKH TXLFN EURZQ IRA MXPSV RYHU WKH ODCB GRJ
```

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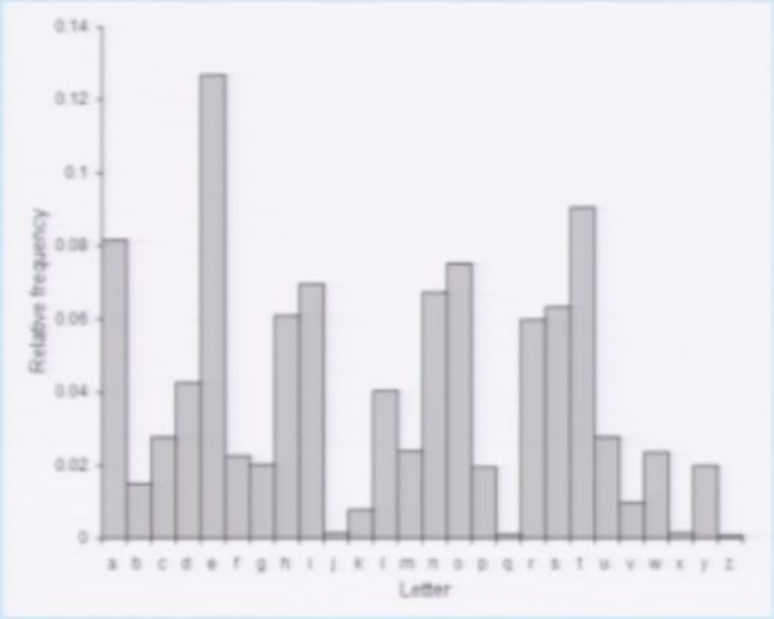
- Many permutations of the alphabet (26!)

Substitution ciphers

- Frequency analysis known as early as 9th century AD



- Compare frequency of letters in ciphertext with that in typical text

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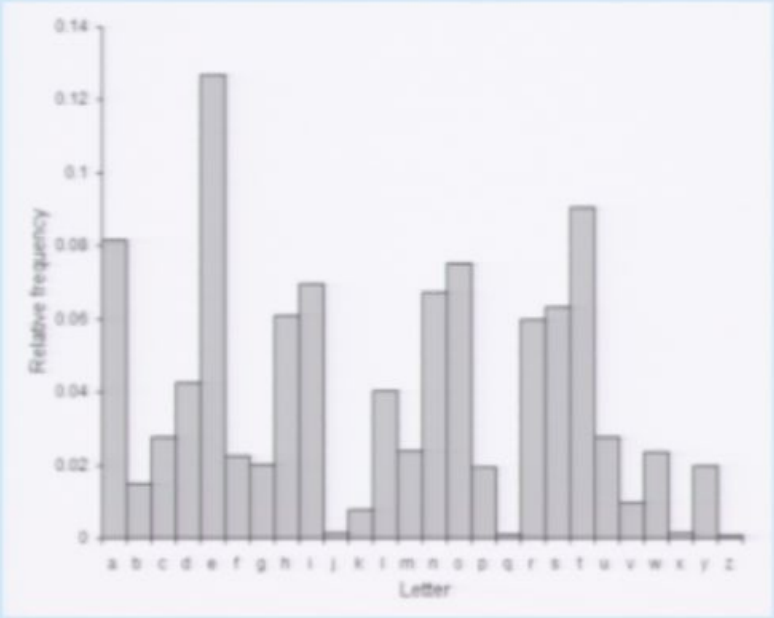
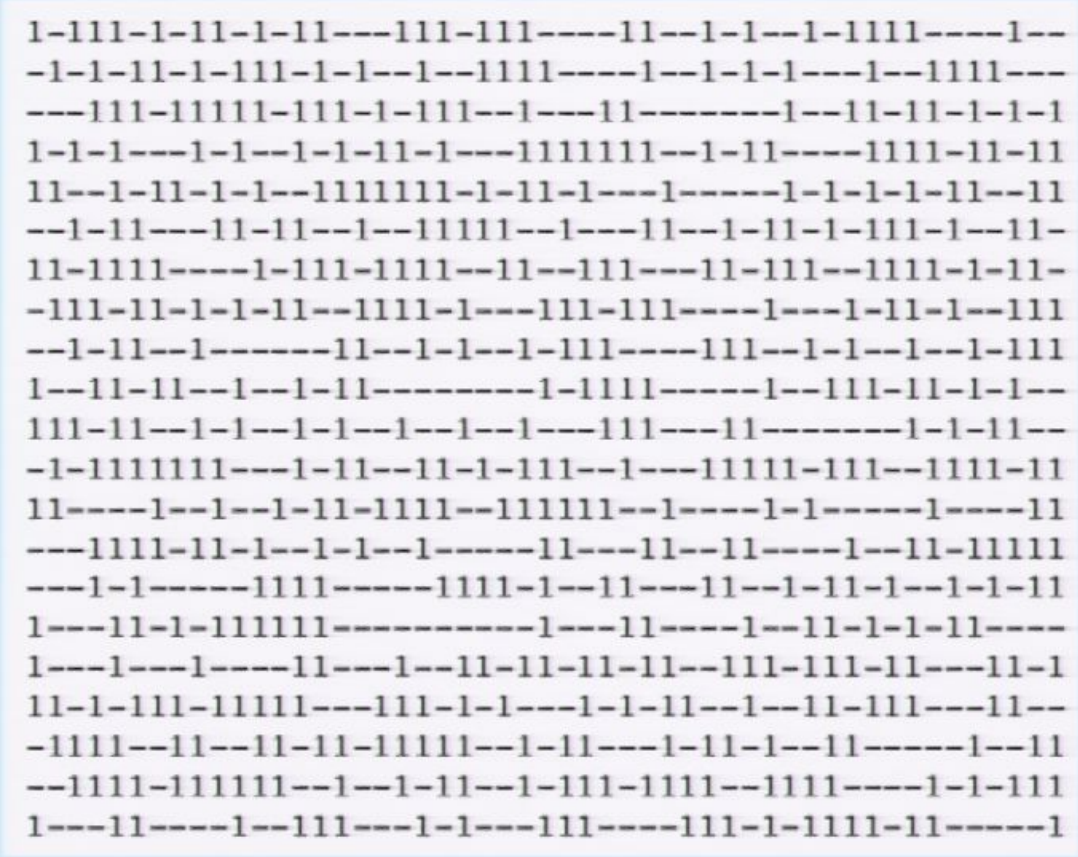


- Compare frequency of letters in ciphertext with that in typical text

Spot the “difference”

Text A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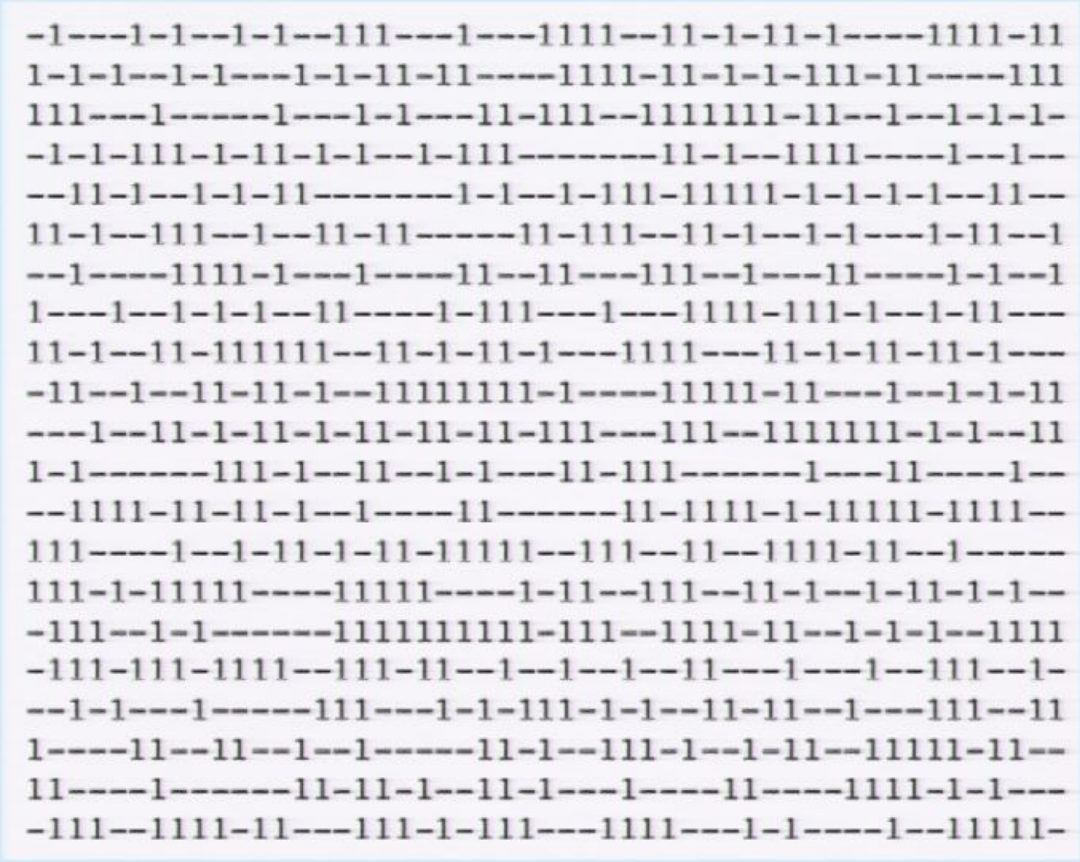
---111-11111-111-1-111--1---11-------1--11-11-1-1-1
1-1-1---1-1--1-1-11-1---1111111--1-11----1111-11-11
11--1-11-1-1--1111111-1-11-1---1-----1-1-1-1-11--11
--1-11---11-11--1--11111--1---11--1-11-1-111-1--11-
11-1111----1-111-1111--11--111---11-111--1111-1-11-
-111-11-1-1-11--1111-1---111-111----1---1-11-1--111
--1-11--1------11--1-1--1-111----111--1-1--1--1-111
1--11-11--1--1-11--------1-1111-----1--111-11-1-1--
111-11--1-1--1-1--1--1--1---111---11-------1-1-11--
-1-1111111---1-11--11-1-111--1---11111-111--1111-11
11----1--1--1-11-1111--111111--1----1-1-----1----11
---1111-11-1--1-1--1-----11---11--11----1--11-11111
---1-1-----1111-----1111-1--11---11--1-11-1--1-1-11
1---11-1-111111----------1---11----1--11-1-1-11----
1---1---1----11---1--11-11-11-11--111-111-11---11-1
11-1-111-11111---111-1-1---1-1-11--1--11-111---11--
-1111--11--11-11-11111--1-11---1-11-1--11-----1--11
--1111-111111--1--1-11--1-111-1111--1111----1-1-111
1---11----1--111---1-1---111----111-1-1111-11-----1

Text B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111---1-----1---1-1---11-111--1111111-11--1--1-1-1-
-1-1-111-1-11-1-1--1-111-------11-1--1111----1--1--
--11-1--1-1-11-------1-1--1-111-11111-1-1-1-1--11--
11-1--111--1--11-11-----11-111--11-1--1-1---1-11--1
--1----1111-1---1----11--11---111--1---11----1-1--1
1---1--1-1-1--11----1-111---1---1111-111-1--1-11---
11-1--11-111111--11-1-11-1---1111---11-1-11-11-1---
-11--1--11-11-1--11111111-1----11111-11---1--1-1-11
---1--11-1-11-1-11-11-11-111---111--1111111-1-1--11
1-1-----111-1--11--1-1---11-111------1---11----1--
--1111-11-11-1--1----11------11-1111-1-11111-1111--
111----1--1-11-1-11-11111--111--11--1111-11--1-----
111-1-11111----11111----1-11--111--11-1--1-11-1-1--
-111--1-1------1111111111-111--1111-11--1-1-1--1111
-111-111-1111--111-11--1--1--1--11---1---1--111--1-
--1-1---1-----111---1-1-111-1-1--11-11--1---111--11
1----11--11--1--1-----11-1--111-1--1-11--11111-11--
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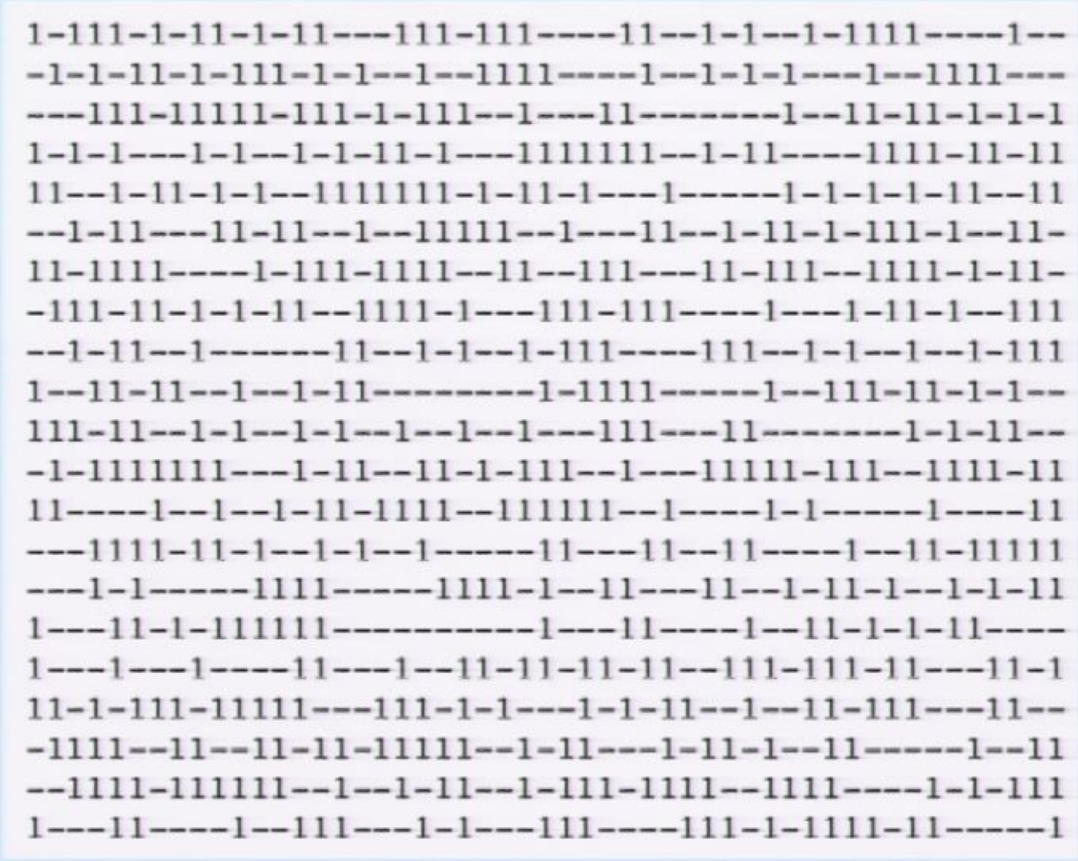
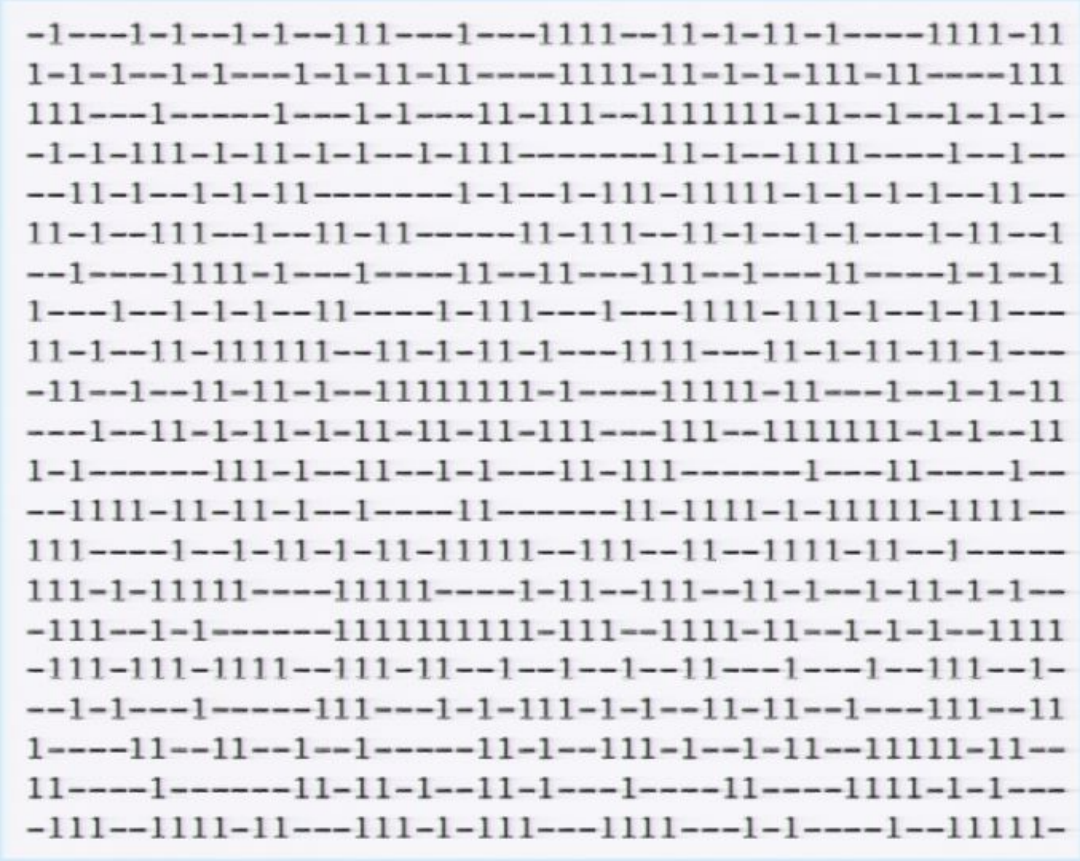
-111--1111-11---111-1-111---1111---1-1----1--11111-

Text A


1-111-1-11-1-11---111-111----11--1-1--1-1111----1--
-1-1-11-1-111-1-1--1--1111----1--1-1-1---1--1111---
---111-11111-111-1-111--1---11-------1--11-11-1-1-1
1-1-1---1-1--1-1-11-1---1111111--1-11----1111-11-11
11--1-11-1-1--1111111-1-11-1---1-----1-1-1-1-11--11
--1-11---11-11--1--11111--1---11--1-11-1-111-1--11-
11-1111----1-111-1111--11--111---11-111--1111-1-11-
-111-11-1-1-11--1111-1---111-111----1---1-11-1--111
--1-11--1------11--1-1--1-111----111--1-1--1--1-111
1--11-11--1--1-11--------1-1111-----1--111-11-1-1--
111-11--1-1--1-1--1--1--1---111---11-------1-1-11--
-1-1111111---1-11--11-1-111--1---11111-111--1111-11
11----1--1--1-11-1111--111111--1----1-1-----1----11
---1111-11-1--1-1--1-----11---11--11----1--11-11111
---1-1-----1111-----1111-1--11---11--1-11-1--1-1-11
1---11-1-111111----------1---11----1--11-1-1-11----
1---1---1----11---1--11-11-11-11--111-111-11---11-1
11-1-111-11111---111-1-1---1-1-11--1--11-111---11--
-1111--11--11-11-11111--1-11---1-11-1--11-----1--11
--1111-111111--1--1-11--1-111-1111--1111----1-1-111
1---11----1--111---1-1---111----111-1-1111-11-----1

Text B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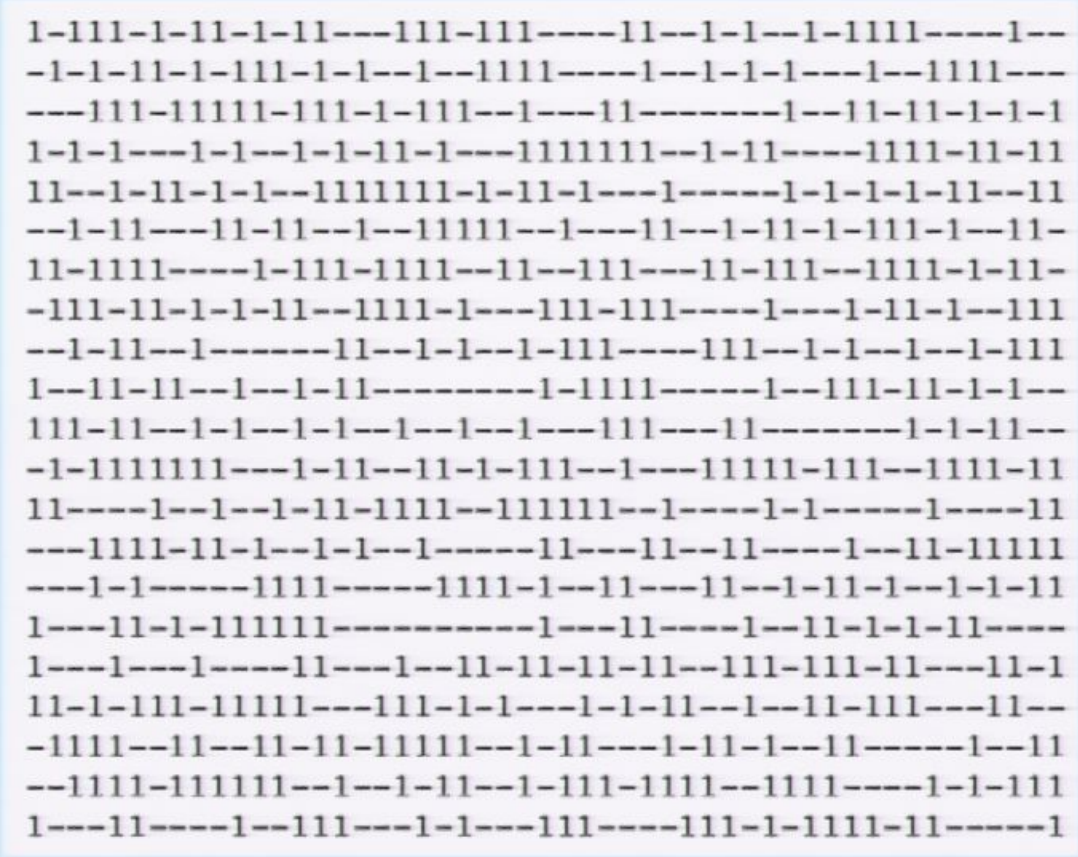
1-1-1--1-1---1-1-11-11----1111-11-1-1-111-11----111
111---1-----1---1-1---11-111--1111111-11--1--1-1-1-
-1-1-111-1-11-1-1--1-111-------11-1--1111----1--1--
--11-1--1-1-11-------1-1--1-111-11111-1-1-1-1--11--
11-1--111--1--11-11-----11-111--11-1--1-1---1-11--1
--1----1111-1---1----11--11---111--1---11----1-1--1
1---1--1-1-1--11----1-111---1---1111-111-1--1-11---
11-1--11-111111--11-1-11-1---1111---11-1-11-11-1---
-11--1--11-11-1--11111111-1----11111-11---1--1-1-11
---1--11-1-11-1-11-11-11-111---111--1111111-1-1--11
1-1-----111-1--11--1-1---11-111------1---11----1--
--1111-11-11-1--1----11------11-1111-1-11111-1111--
111----1--1-11-1-11-11111--111--11--1111-11--1-----
111-1-11111----11111----1-11--111--11-1--1-11-1-1--
-111--1-1------1111111111-111--1111-11--1-1-1--1111
-111-111-1111--111-11--1--1--1--11---1---1--111--1-
--1-1---1-----111---1-1-111-1-1--11-11--1---111--11
1----11--11--1--1-----11-1--111-1--1-11--11111-11--
11----1------11-11-1--11-1---1----11----1111-1-1---
-111--1111-11---111-1-111---1111---1-1----1--11111-

Text A


1-111-1-11-1-11---111-111----11--1-1--1-1111----1--
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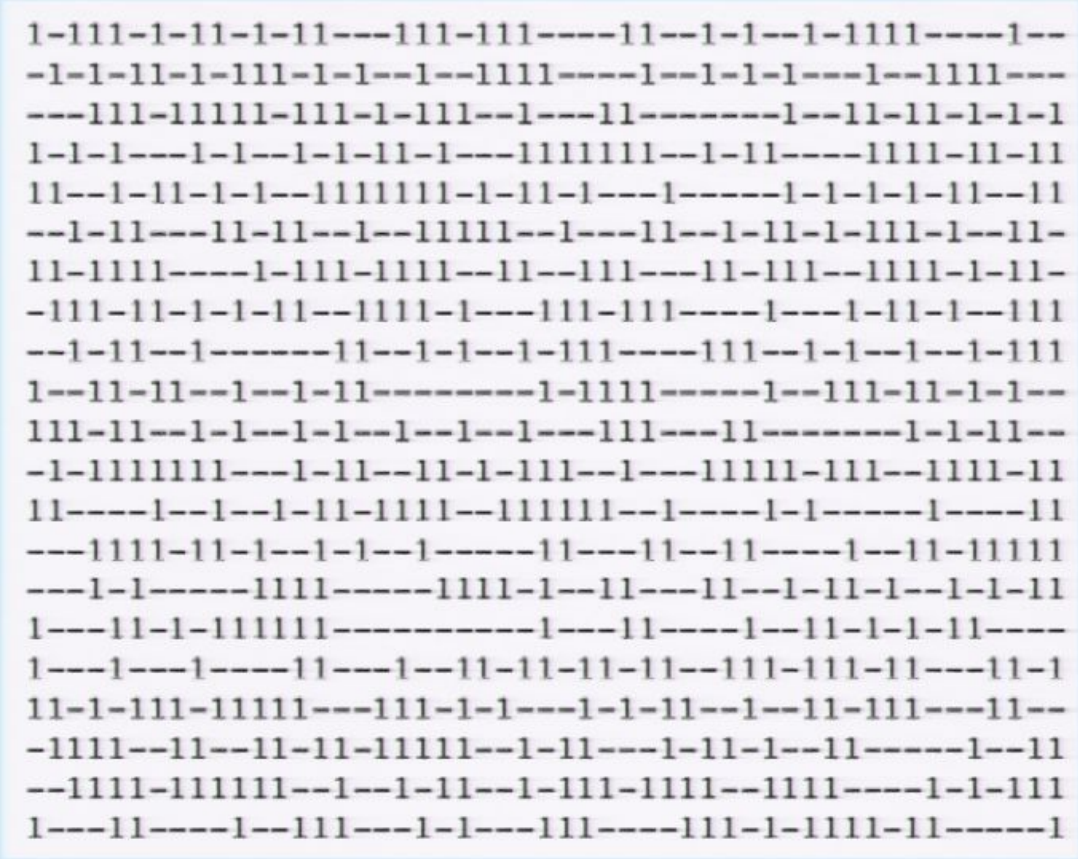
---111-11111-111-1-111--1---11-------1--11-11-1-1-1
1-1-1---1-1--1-1-11-1---1111111--1-11----1111-11-11
11--1-11-1-1--1111111-1-11-1---1-----1-1-1-1-11--11
--1-11---11-11--1--11111--1---11--1-11-1-111-1--11-
11-1111----1-111-1111--11--111---11-111--1111-1-11-
-111-11-1-1-11--1111-1---111-111----1---1-11-1--111
--1-11--1------11--1-1--1-111----111--1-1--1--1-111
1--11-11--1--1-11--------1-1111-----1--111-11-1-1--
111-11--1-1--1-1--1--1--1---111---11-------1-1-11--
-1-1111111---1-11--11-1-111--1---11111-111--1111-11
11----1--1--1-11-1111--111111--1----1-1-----1----11
---1111-11-1--1-1--1-----11---11--11----1--11-11111
---1-1-----1111-----1111-1--11---11--1-11-1--1-1-11
1---11-1-111111----------1---11----1--11-1-1-11----
1---1---1----11---1--11-11-11-11--111-111-11---11-1
11-1-111-11111---111-1-1---1-1-11--1--11-111---11--
-1111--11--11-11-11111--1-11---1-11-1--11-----1--11
--1111-111111--1--1-11--1-111-1111--1111----1-1-111
1---11----1--111---1-1---111----111-1-1111-11-----1

Text A



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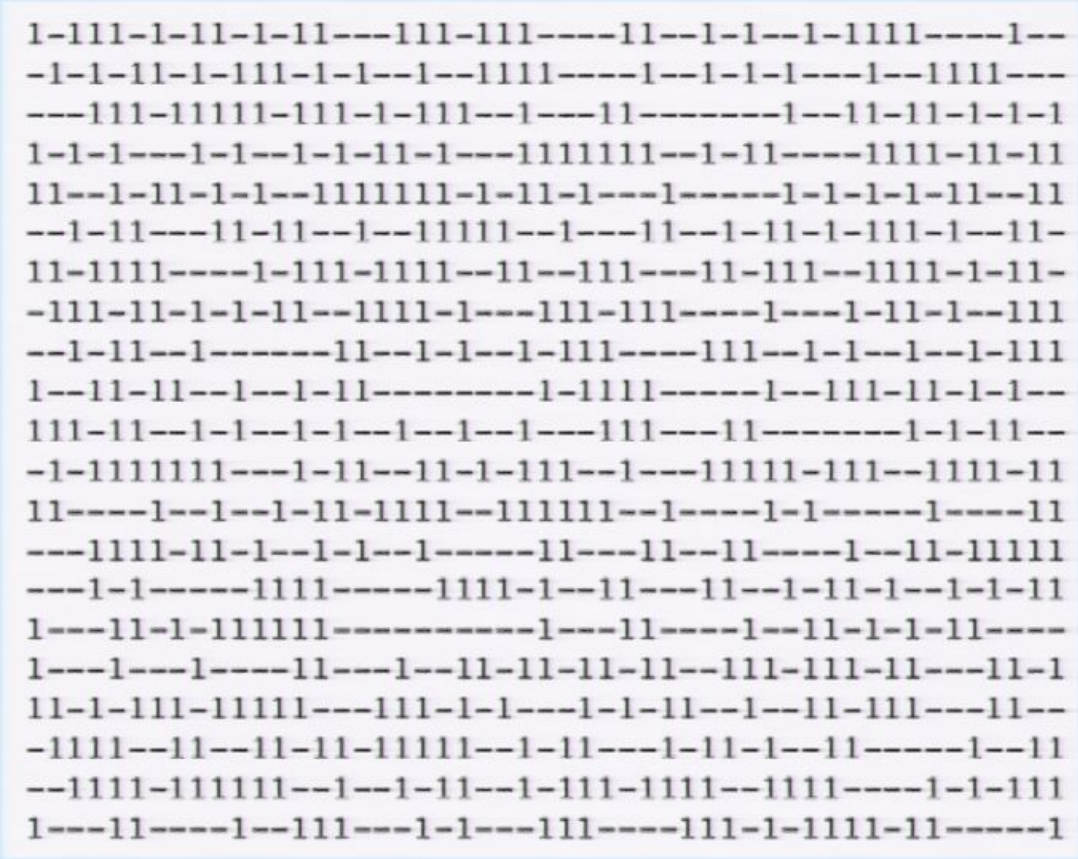
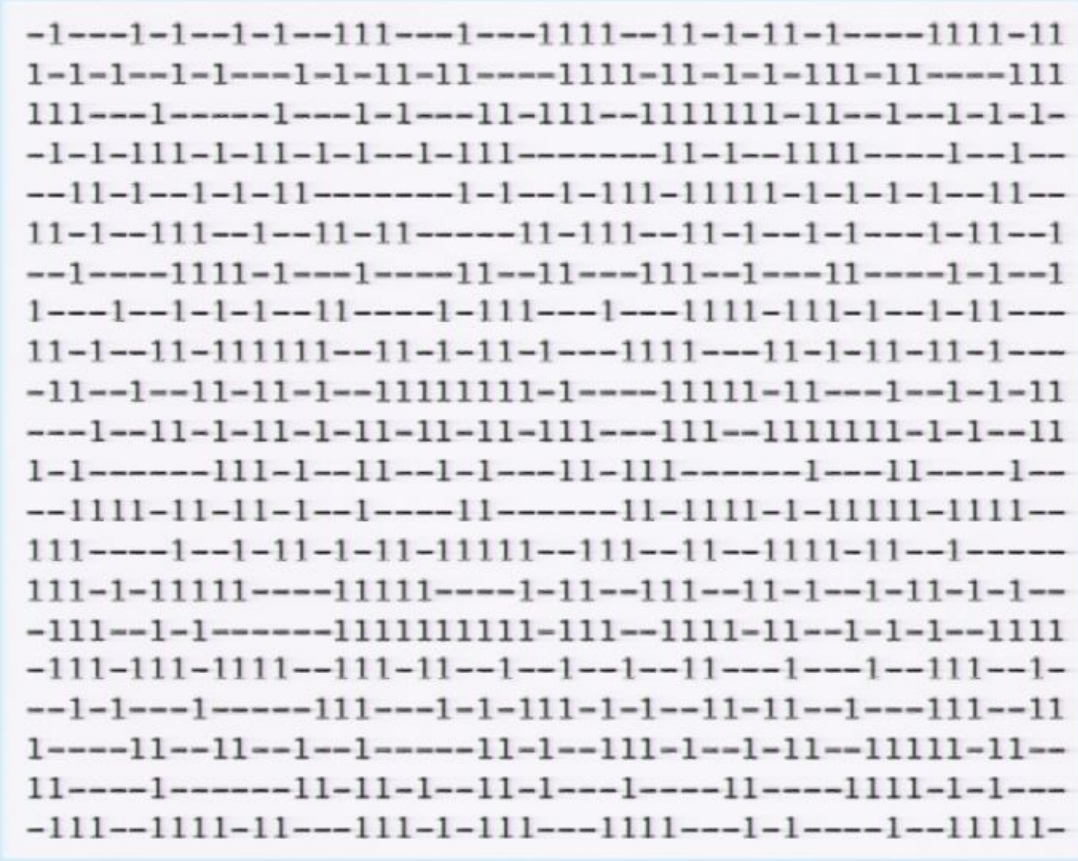


Text B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1-1-1--1-1---1-1-11-11----1111-11-1-1-111-11----111
111---1-----1---1-1---11-111--1111111-11--1--1-1-1-
-1-1-111-1-11-1-1--1-111-------11-1--1111----1--1--
--11-1--1-1-11-------1-1--1-111-11111-1-1-1-1--11--
11-1--111--1--11-11-----11-111--11-1--1-1---1-11--1
--1----1111-1---1----11--11---111--1---11----1-1--1
1---1--1-1-1--11----1-111---1---1111-111-1--1-11---
11-1--11-111111--11-1-11-1---1111---11-1-11-11-1---
-11--1--11-11-1--11111111-1----11111-11---1--1-1-11
---1--11-1-11-1-11-11-11-111---111--1111111-1-1--11
1-1-----111-1--11--1-1---11-111------1---11----1--
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111----1--1-11-1-11-11111--111--11--1111-11--1-----
111-1-11111----11111----1-11--111--11-1--1-11-1-1--
-111--1-1------1111111111-111--1111-11--1-1-1--1111
-111-111-1111--111-11--1--1--1--11---1---1--111--1-
--1-1---1-----111---1-1-111-1-1--11-11--1---111--11
1----11--11--1--1-----11-1--111-1--1-11--11111-11--
11----1------11-11-1--11-1---1----11----1111-1-1---
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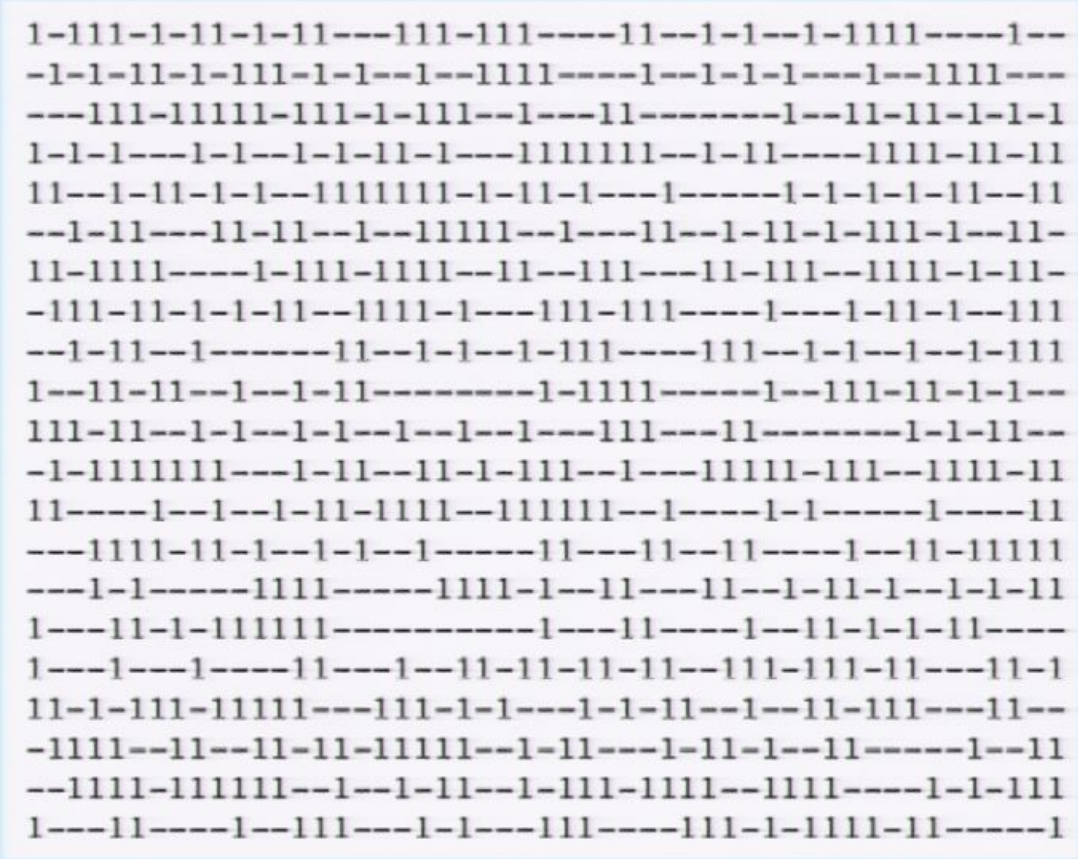
Text A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---111-11111-111-1-111--1---11-------1--11-11-1-1-1
1-1-1---1-1--1-1-11-1---1111111--1-11----1111-11-11
11--1-11-1-1--1111111-1-11-1---1-----1-1-1-1-11--11
--1-11---11-11--1--11111--1---11--1-11-1-111-1--11-
11-1111----1-111-1111--11--111---11-111--1111-1-11-
-111-11-1-1-11--1111-1---111-111----1---1-11-1--111
--1-11--1------11--1-1--1-111----111--1-1--1--1-111
1--11-11--1--1-11--------1-1111-----1--111-11-1-1--
111-11--1-1--1-1--1--1--1---111---11-------1-1-11--
-1-1111111---1-11--11-1-111--1---11111-111--1111-11
11----1--1--1-11-1111--111111--1----1-1-----1----11
---1111-11-1--1-1--1-----11---11--11----1--11-11111
---1-1-----1111-----1111-1--11---11--1-11-1--1-1-11
1---11-1-111111----------1---11----1--11-1-1-11----
1---1---1----11---1--11-11-11-11--111-111-11---11-1
11-1-111-11111---111-1-1---1-1-11--1--11-111---11--
-1111--11--11-11-11111--1-11---1-11-1--11-----1--11
--1111-111111--1--1-11--1-111-1111--1111----1-1-111
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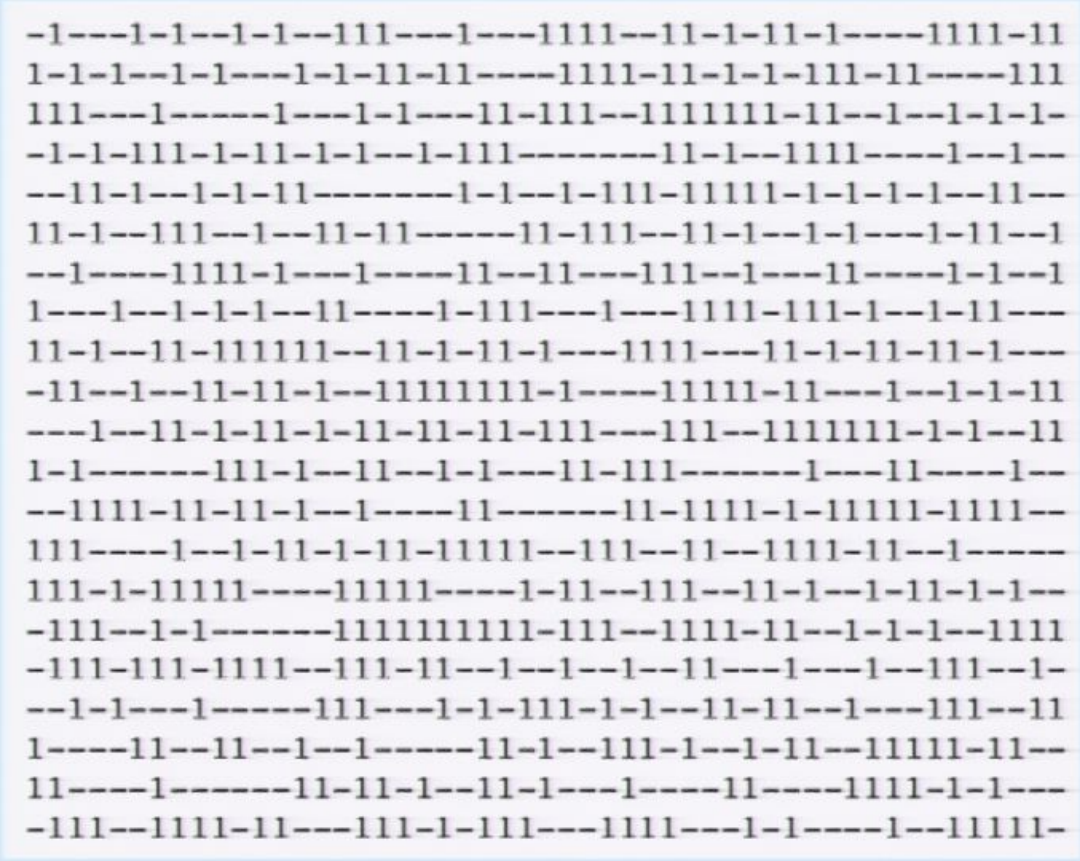
Text B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1-1-1--1-1---1-1-11-11----1111-11-1-1-111-11----111
111---1-----1---1-1---11-111--1111111-11--1--1-1-1-
-1-1-111-1-11-1-1--1-111-------11-1--1111----1--1--
--11-1--1-1-11-------1-1--1-111-11111-1-1-1-1--11--
11-1--111--1--11-11-----11-111--11-1--1-1---1-11--1
--1----1111-1---1----11--11---111--1---11----1-1--1
1---1--1-1-1--11----1-111---1---1111-111-1--1-11---
11-1--11-111111--11-1-11-1---1111---11-1-11-11-1---
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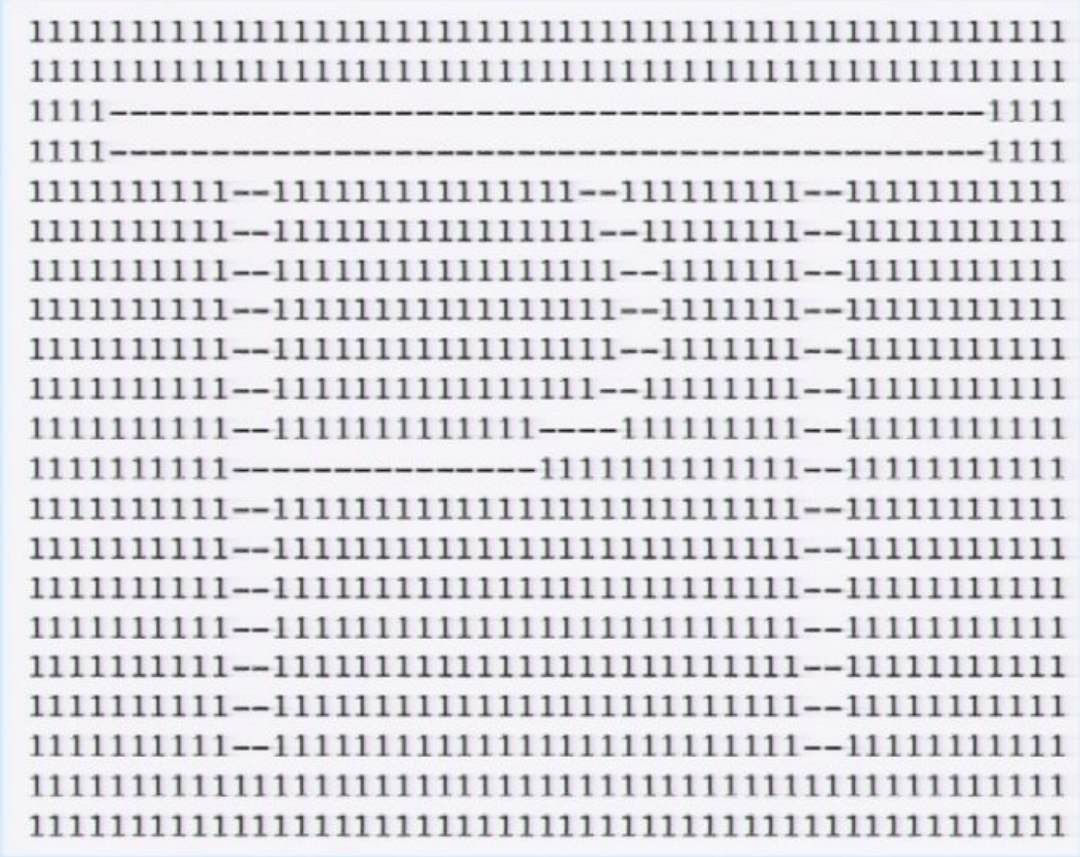
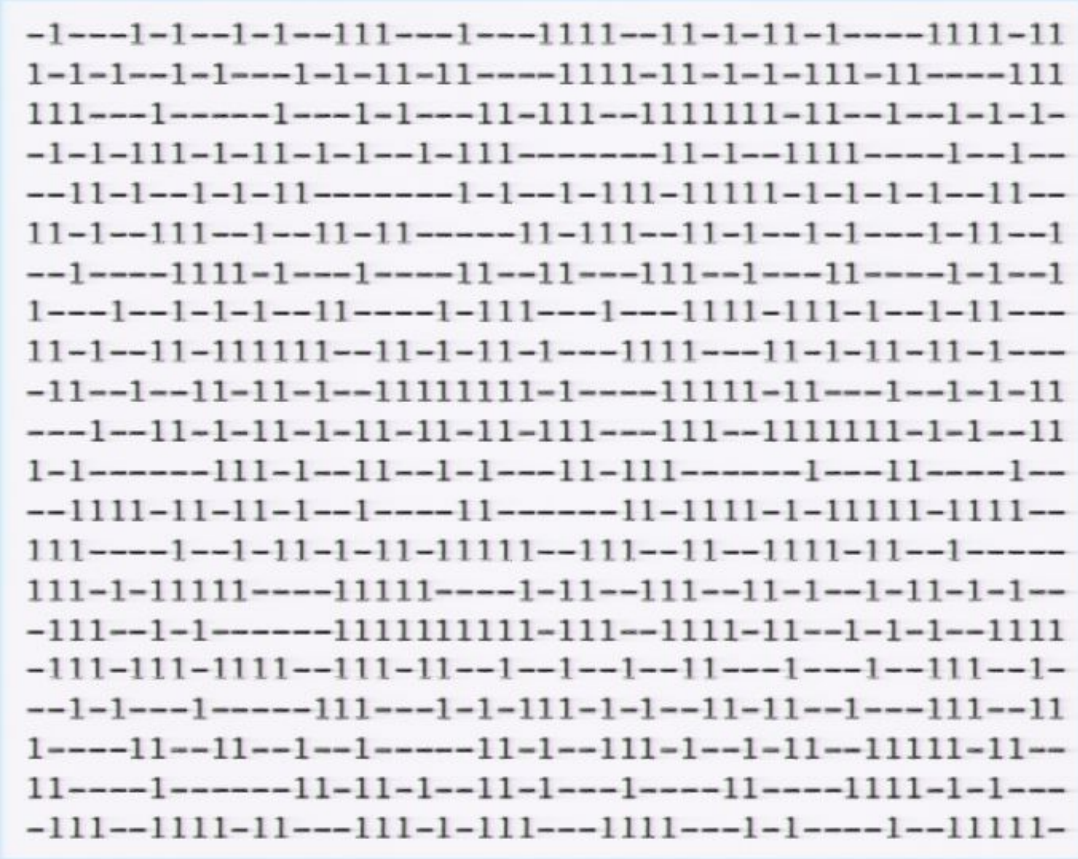
---1--11-1-11-1-11-11-11-111---111--1111111-1-1--11
1-1-----111-1--11--1-1---11-111------1---11----1--
--1111-11-11-1--1----11------11-1111-1-11111-1111--
111----1--1-11-1-11-11111--111--11--1111-11--1-----
111-1-11111----11111----1-11--111--11-1--1-11-1-1--
-111--1-1------1111111111-111--1111-11--1-1-1--1111
-111-111-1111--111-11--1--1--1--11---1---1--111--1-
--1-1---1-----111---1-1-111-1-1--11-11--1---111--11
1----11--11--1--1-----11-1--111-1--1-11--11111-11--
11----1------11-11-1--11-1---1----11----1111-1-1---
-111--1111-11---111-1-111---1111---1-1----1--11111-

“Difference”



Text B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111---1-----1---1-1---11-111--1111111-11--1--1-1-1-
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--11-1--1-1-11-------1-1--1-111-11111-1-1-1-1--11--
11-1--111--1--11-11-----11-111--11-1--1-1---1-11--1
--1----1111-1---1----11--11---111--1---11----1-1--1
1---1--1-1-1--11----1-111---1---1111-111-1--1-11---
11-1--11-111111--11-1-11-1---1111---11-1-11-11-1---
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---1--11-1-11-1-11-11-11-111---111--1111111-1-1--11
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-111--1-1------1111111111-111--1111-11--1-1-1--1111
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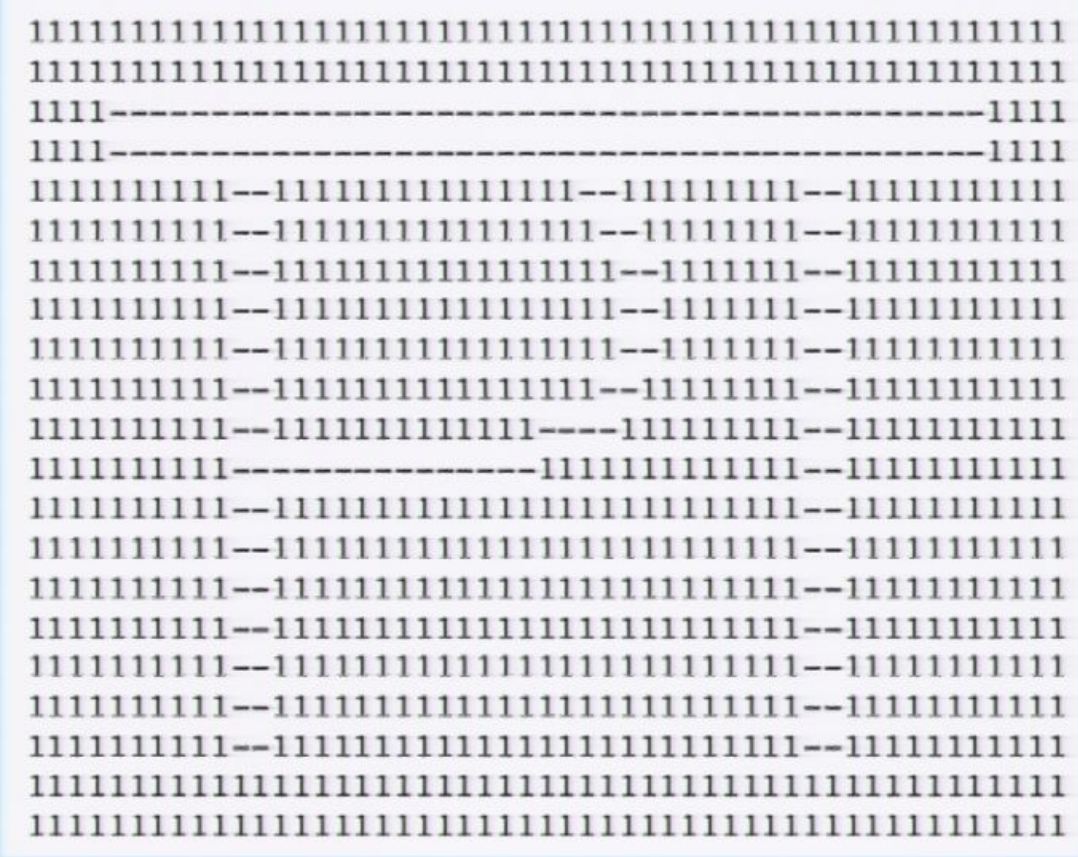
--1-1---1-----111---1-1-111-1-1--11-11--1---111--11
1----11--11--1--1-----11-1--111-1--1-11--11111-11--
11----1------11-11-1--11-1---1----11----1111-1-1---
-111--1111-11---111-1-111---1111---1-1----1--11111-

“Difference”


1111111111111111111111111111111111111111111111111111
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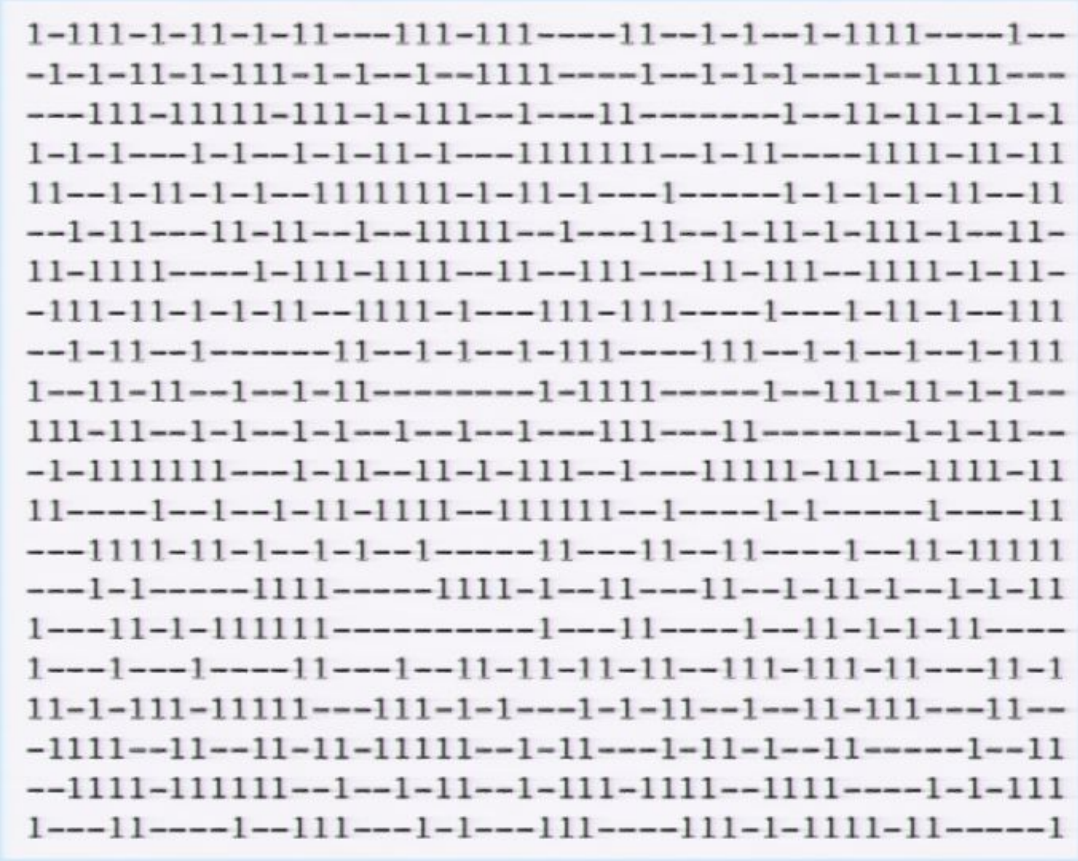
Text A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---111-11111-111-1-111--1---11-------1--11-11-1-1-1
1-1-1---1-1--1-1-11-1---1111111--1-11----1111-11-11
11--1-11-1-1--1111111-1-11-1---1-----1-1-1-1-11--11
--1-11---11-11--1--11111--1---11--1-11-1-111-1--11-
11-1111----1-111-1111--11--111---11-111--1111-1-11-
-111-11-1-1-11--1111-1---111-111----1---1-11-1--111
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---1111-11-1--1-1--1-----11---11--11----1--11-11111
---1-1-----1111-----1111-1--11---11--1-11-1--1-1-11
1---11-1-111111----------1---11----1--11-1-1-11----
1---1---1----11---1--11-11-11-11--111-111-11---11-1
11-1-111-11111---111-1-1---1-1-11--1--11-111---11--
-1111--11--11-11-11111--1-11---1-11-1--11-----1--11
--1111-111111--1--1-11--1-111-1111--1111----1-1-111
1---11----1--111---1-1---111----111-1-1111-11-----1

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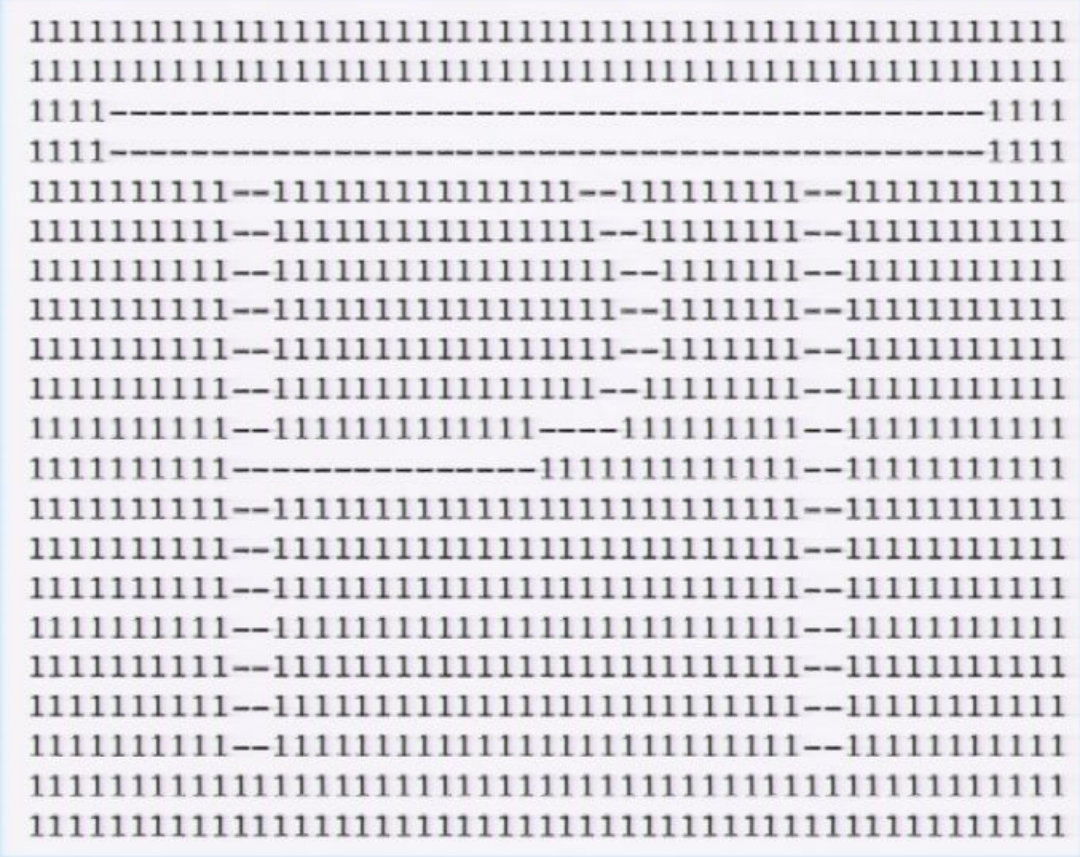
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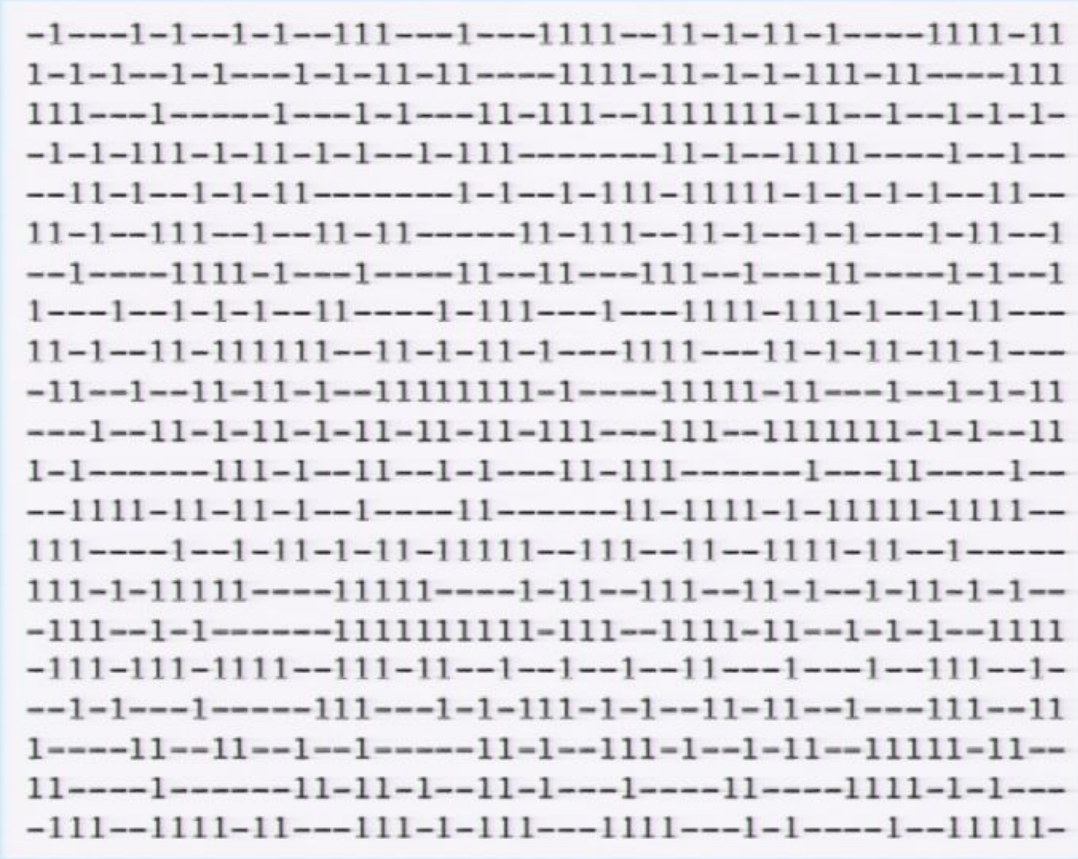
Text B


-1---1-1--1-1--111---1---1111--11-1-11-1----1111-11
1-1-1--1-1---1-1-11-11----1111-11-1-1-111-11----111
111---1-----1---1-1---11-111--1111111-11--1--1-1-1-
-1-1-111-1-11-1-1--1-111-------11-1--1111----1--1--
--11-1--1-1-11-------1-1--1-111-11111-1-1-1-1--11--
11-1--111--1--11-11-----11-111--11-1--1-1---1-11--1
--1----1111-1---1----11--11---111--1---11----1-1--1
1---1--1-1-1--11----1-111---1---1111-111-1--1-11---
11-1--11-111111--11-1-11-1---1111---11-1-11-11-1---
-11--1--11-11-1--11111111-1----11111-11---1--1-1-11
---1--11-1-11-1-11-11-11-111---111--1111111-1-1--11
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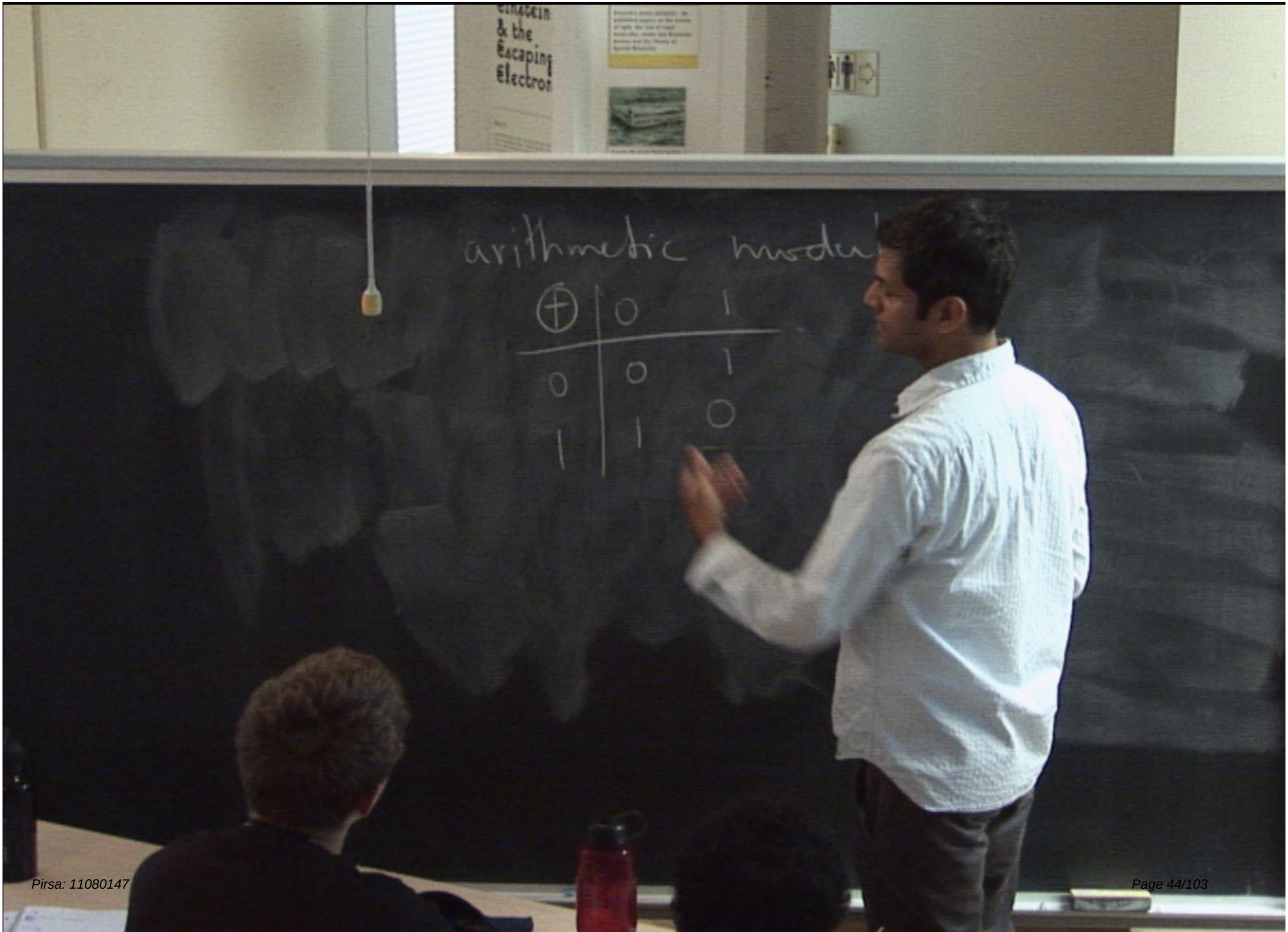
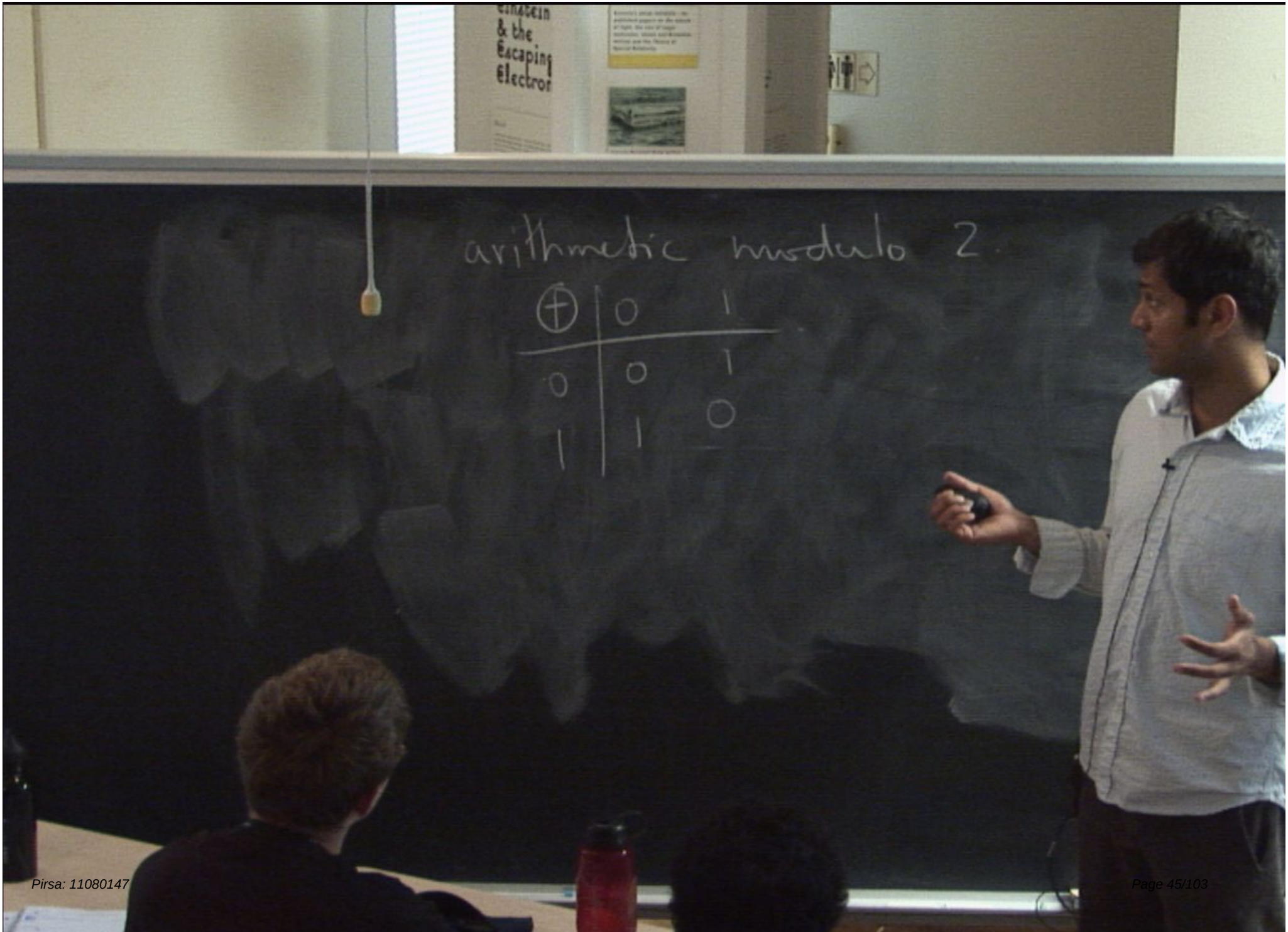
111-1-11111----11111----1-11--111--11-1--1-11-1-1--
-111--1-1------1111111111-111--1111-11--1-1-1--1111
-111-111-1111--111-11--1--1--1--11---1---1--111--1-
--1-1---1-----111---1-1-111-1-1--11-11--1---111--11
1----11--11--1--1-----11-1--111-1--1-11--11111-11--
11----1------11-11-1--11-1---1----11----1111-1-1---
-111--1111-11---111-1-111---1111---1-1----1--11111-


PERIMETER
INSTITUTE FOR THEORETICAL PHYSICS


& the
Escaping
Electron
arithmetic
⊕ 0 1
0 0 1
1 1 0


& the
Escaping
Electron
arithmetic modulo 2
⊕ 0 1
0 0 1
1 1 0

Vernam cipher

- Idea: make ciphertext look random to others
- Alice and Bob keep outcome k of coin toss (0/1)
- Let Alice's message be a single bit m (0/1)
- Ciphertext $c = m \oplus k$

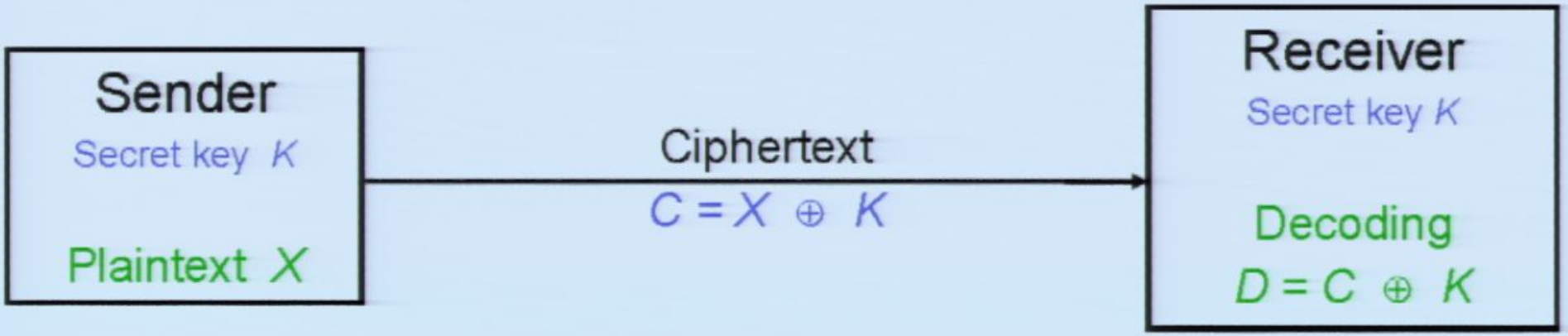
$m \setminus k$	0	1
0	0	1
1	1	0

Security

$m \setminus k$	0	1
0	0	1
1	1	0

- If k is 0 or 1 with probability 1/2, so is c !
- Ciphertext is random to all but Alice and Bob
- Bob can recover $m = c \oplus k$
- Generalizes to longer messages (apply to every bit)

Private key encryption



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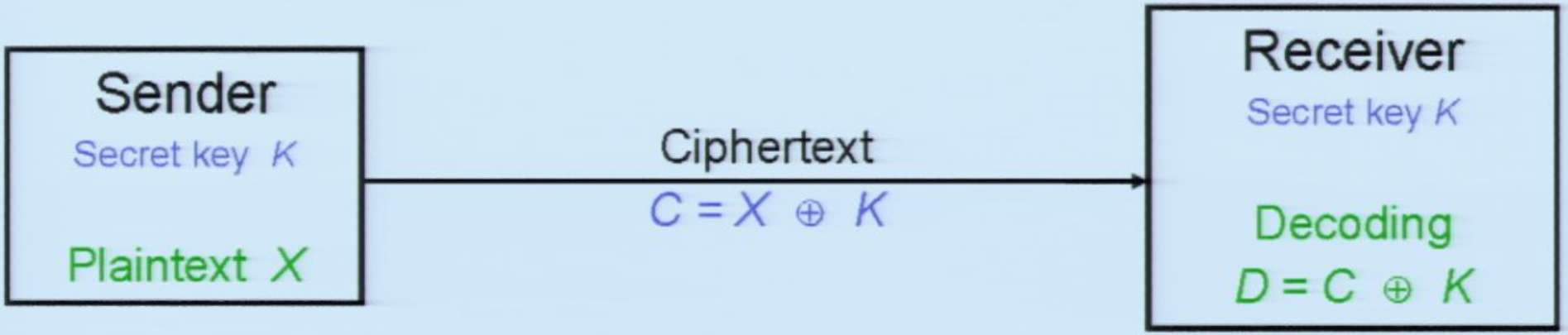

Secure, unless eavesdropper knows the random key

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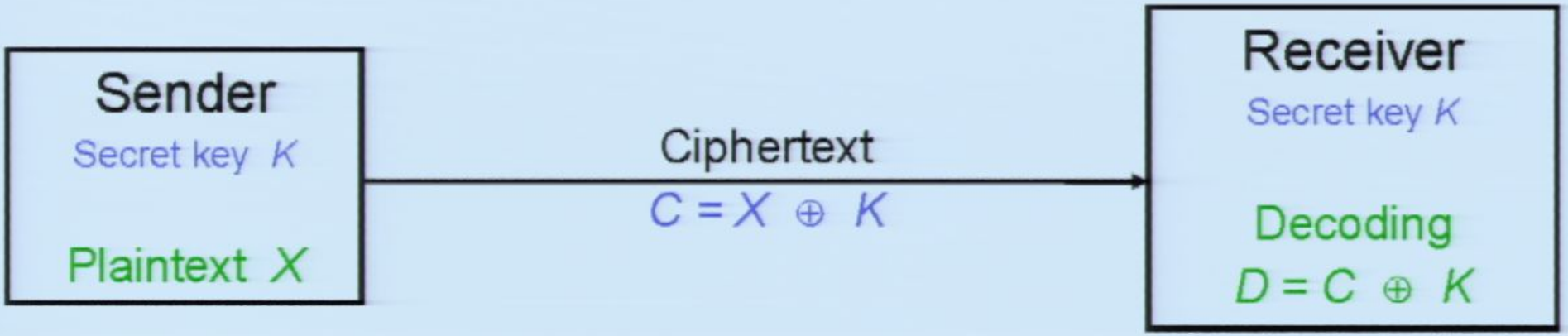
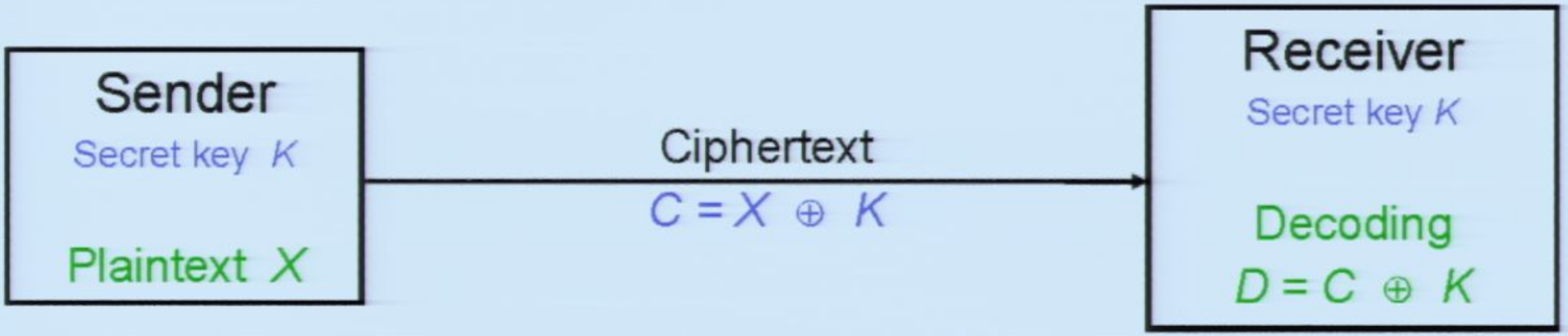


Secure, unless eavesdropper knows the random key

[Shannon 1949]

Disadvantages:

Private key encryption



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(1) n users $\rightarrow n(n-1)/2$ keys

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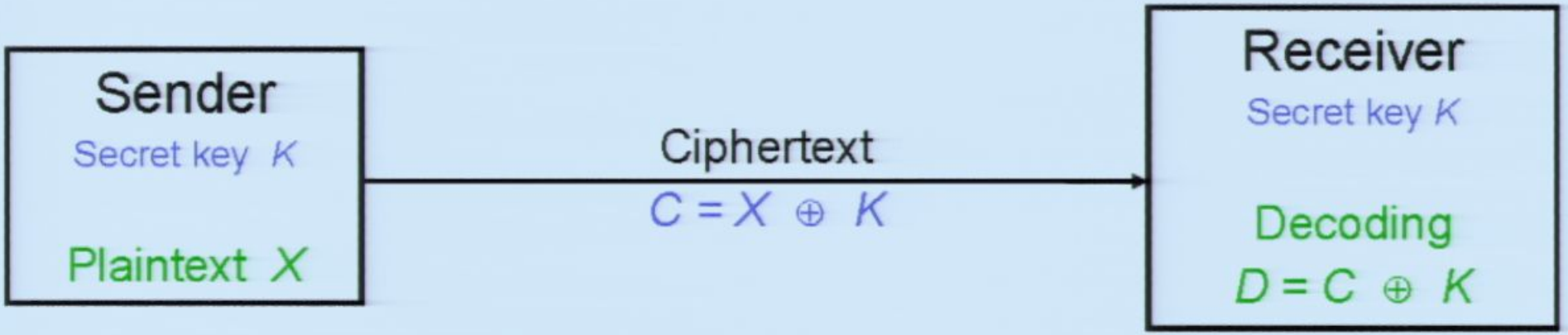

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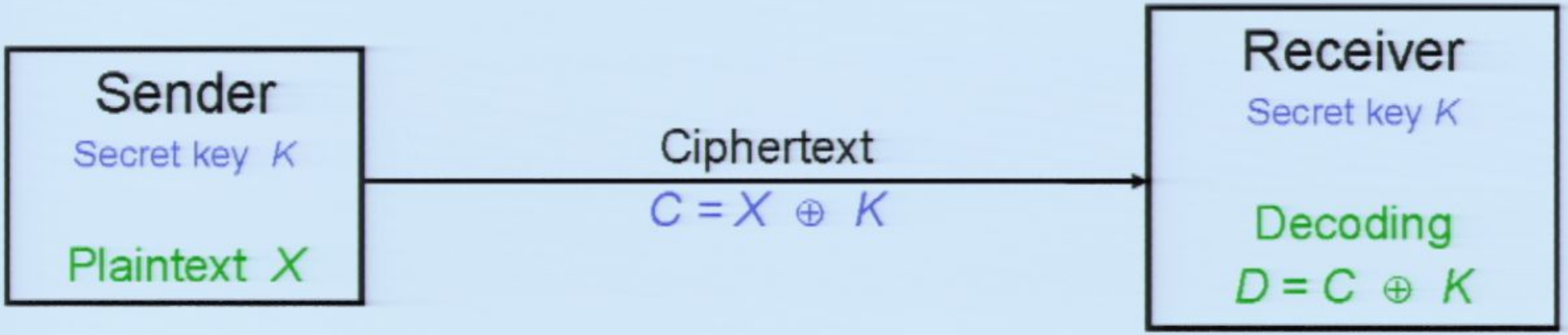

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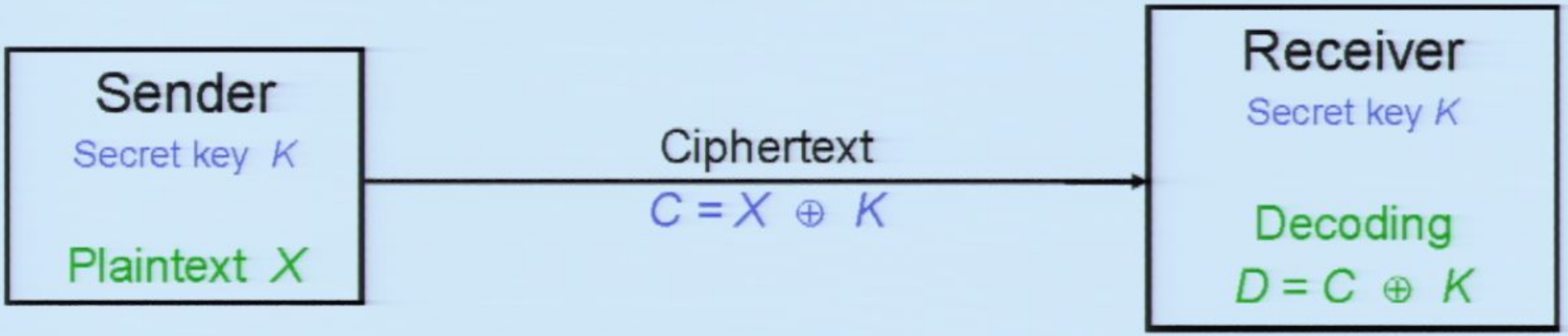
Private key encryption



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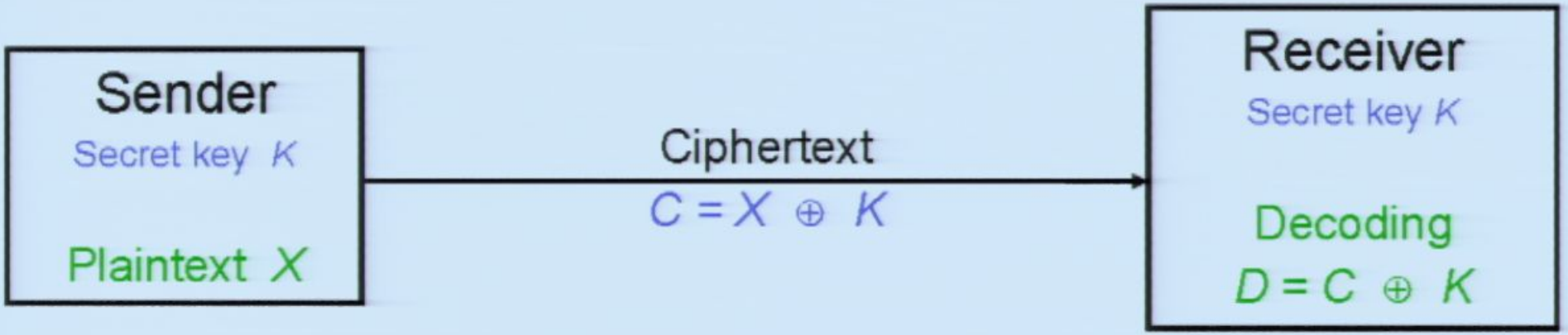

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Use of photon polarization

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- Internet transactions are based on public key encryption
- Assumes computational hardness of factorizing large integers into their prime factors

- Using polarized light, we can establish a secure random key: an eavesdropper provably has little information about the key

Quantum key distribution [Bennett, Brassard'84]

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- Assume Alice and Bob want 1 bit of key

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- She prepares a single photon of light with the corresponding polarization, sends it to Bob

Encoding a bit into polarization

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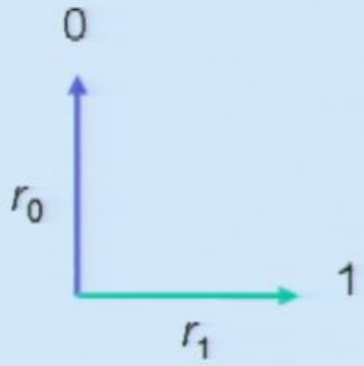
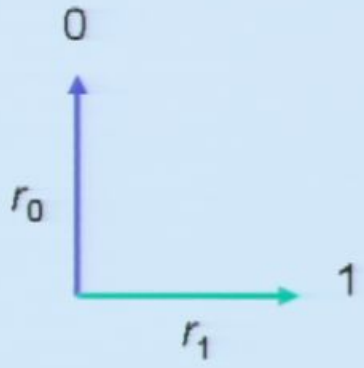
Rectilinear

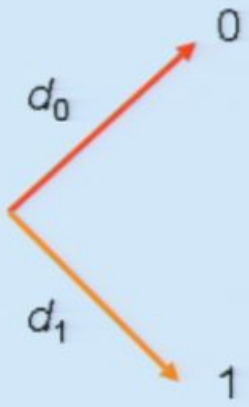


Encoding a bit into polarization

Rectilinear



Diagonal



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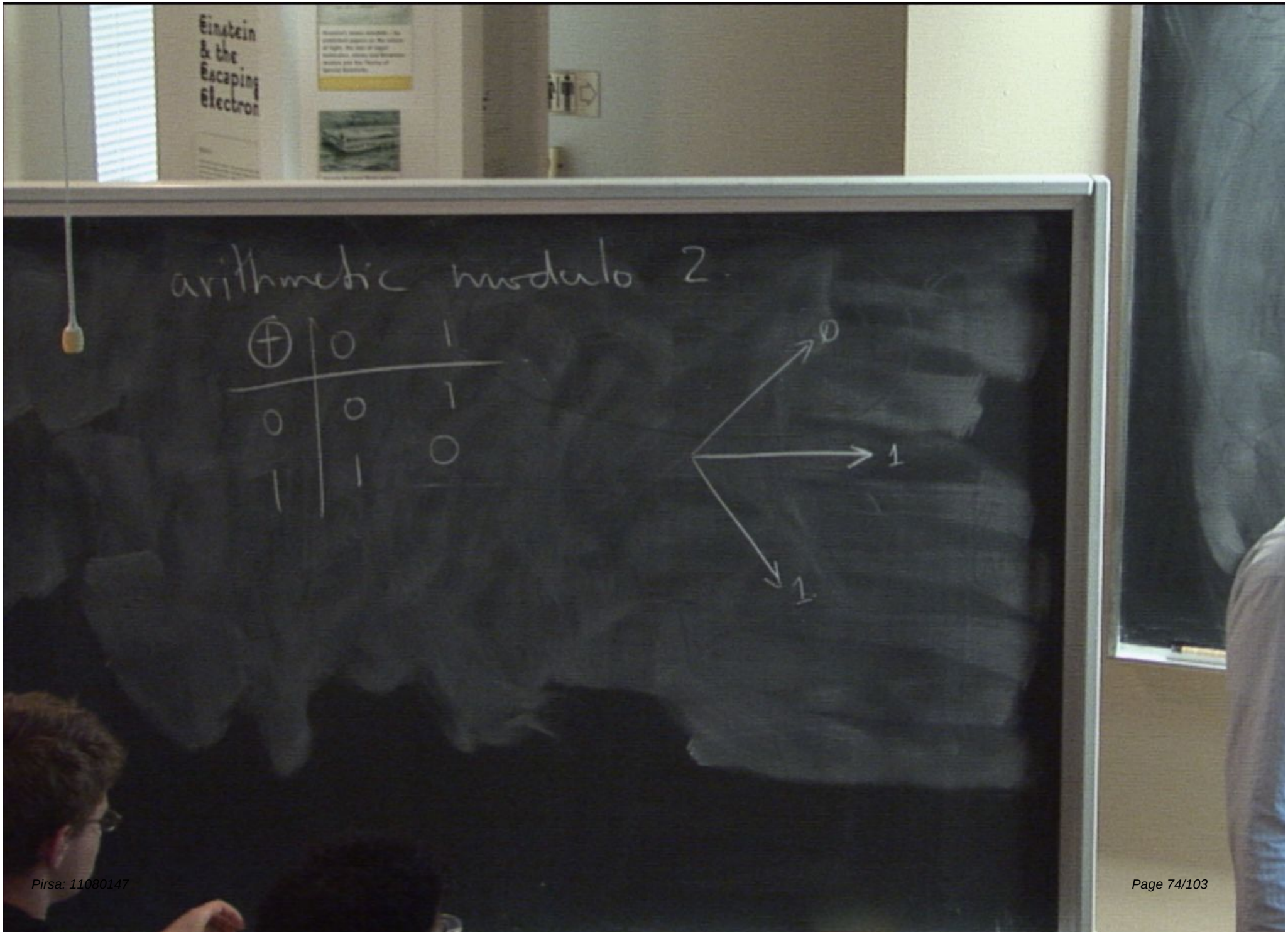
Einstein
& the
Escaping
Electron
arithmetic modulo 2
⊕ | 0 1
0 | 0 1
1 | 1 0
0
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1

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  Bob knows if he got the key bit

- If there is no eavesdropping, they have a random bit

Security against eavesdropping

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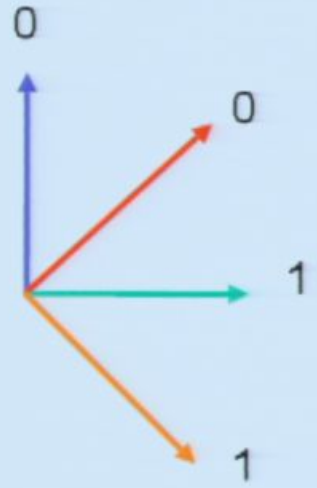
- If Eve tries to measure polarization, she likely alters it



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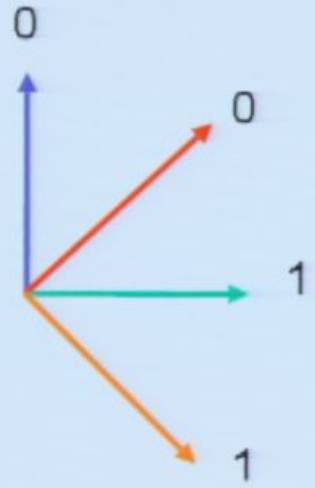

- Alice and Bob try to detect errors
  - Repeat encoding procedure for many key bits
  - Pick random subset for testing: Alice announces the key bit as well, and Bob checks for tampering
  - If too many bits are corrupted, they restart the protocol

Security…

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- Prototypes at IQC (over fibre); and between IQC and PI over free space

What else?

Karpov ⟷ Kasparov

Phone line

- Who plays white?
- Coin-flipping:

  follow some randomized procedure such that
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Karpov ⟷ Kasparov

Phone line

- Who plays white?
- Coin-flipping:

  follow some randomized procedure such that
  - If both are honest, outcome is unbiased
  - If any one is dishonest and the other honest, outcome is heads or tails with probability at most ½.

    (the honest party may cry "foul")

A quantum proposal

- Karpov:

  Picks a random orientation a

  $a = 0 \leftrightarrow$ rectilinear $\quad a = 1 \leftrightarrow$ diagonal

Quantum protocol…

- Second step: Kasparov

  Picks a random bit b,

  sends bit to Karpov

- Third step: Karpov

  Reveals orientation a, and polarization φ

- Fourth step: Kasparov

  Checks if photon received is in claimed polarization. If not, cries "foul", and quits.

- Finally (no foul): both agree on outcome $a \oplus b$

With one dishonest player…

- Karpov:

  Once he sends a photon in a chosen polarization, he cannot change it

Security

Security

Secure if Kasparov tries to cheat, but...

...there is a subtle quantum strategy for Karpov:

1. Prepares a pair of photons with correlated polarization

$$(1/\sqrt{2}) \quad [\,(r_0, r_0) + (r_1, r_1)\,].$$

Sends one photon to Kasparov.

2. When $b = 0$, measures his photon in the rectilinear basis.
Claims $a = 0$, $\varphi =$ observed polarization

Bias of outcome

When $b = 1$…

$$(1/\sqrt{2}) \quad [\,(r_0, r_0) \;+\; (r_1, r_1)\,]$$

$$= (1/2\sqrt{2}) \quad [\,(d_0 - d_1, d_0 - d_1) \;+\; (d_0 + d_1, d_0 + d_1)]$$

Quantum coin-flipping

- This, and *all* other conceivable protocols are doomed to fail; ideal quantum coin-flipping is impossible

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- Not all tasks are realizable
- Development of new protocols important in light of quantum attacks on existing public-key systems