

# Introduction

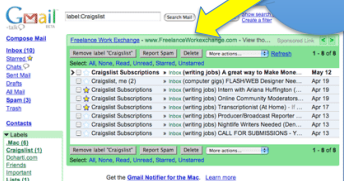
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School of Informatics  
University of Edinburgh

January 16, 2014

# The first half of this course (Weeks 1-5) is about

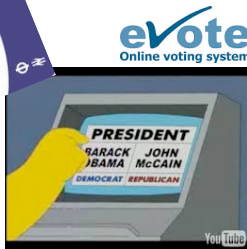


INTERNET



exchanging data **“securely”** over a **public medium**

# Many applications rely on “securely” exchanged data



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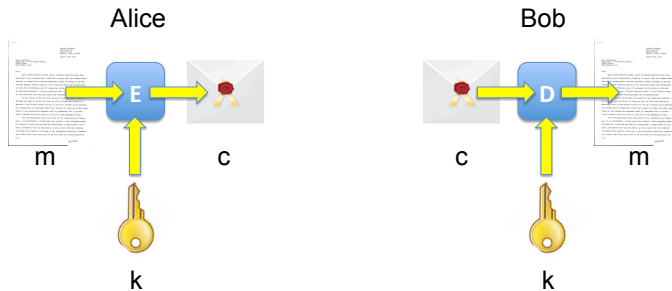
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- ▶ ...

# Cryptographic primitives

# Symmetric ciphers

- ▶ encryption algorithm  $E : \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{C}$   
decryption algorithm  $D : \mathcal{K} \times \mathcal{C} \rightarrow \mathcal{M}$   
st.  $\forall k \in \mathcal{K}$ , and  $\forall m \in \mathcal{M}$ ,  $D(k, E(k, m)) = m$

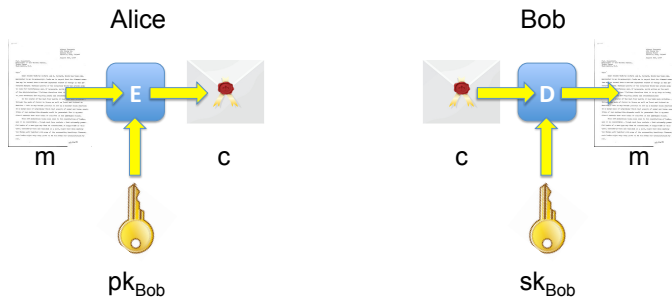


- ▶ same key  $k$  to encrypt and decrypt
- ▶ the key  $k$  is secret: only known to Alice and Bob

Examples: One-time pad, DES, AES, ...

# Asymmetric ciphers

- ▶ key generation algorithm:  $G : \rightarrow \mathcal{K} \times \mathcal{K}$
- encryption algorithm  $E : \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{C}$
- decryption algorithm  $D : \mathcal{K} \times \mathcal{C} \rightarrow \mathcal{M}$
- st.  $\forall (sk, pk) \in G$ , and  $\forall m \in \mathcal{M}$ ,  $D(sk, E(pk, m)) = m$

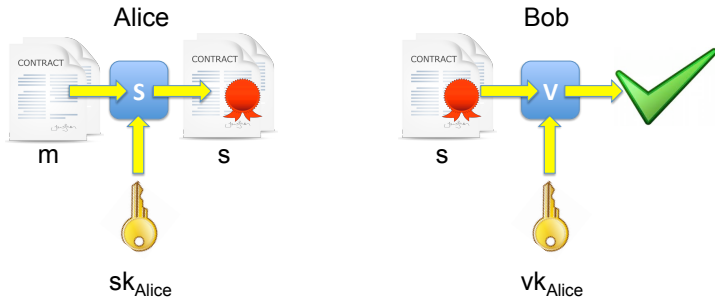


- ▶ the decryption key  $sk$  is secret (only known to Bob). The encryption key  $pk$  is known to everyone. And  $sk \neq pk$

Examples: RSA, ElGamal, Diffie-Hellman, ...

# Digital signatures

- ▶ key generation algorithm:  $G : \rightarrow \mathcal{K} \times \mathcal{K}$   
signing algorithm  $S : \mathcal{K} \times \mathcal{M} \rightarrow \mathcal{S}$   
verification algorithm  $V : \mathcal{K} \times \mathcal{S} \rightarrow \{\top, \perp\}$   
st.  $\forall (sk, vk) \in G$ , and  $\forall m \in \mathcal{M}$ ,  $V(vk, S(sk, m)) = \top$

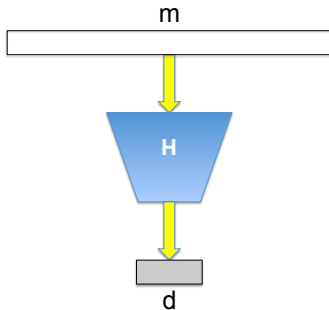


- ▶ the signing key  $sk$  is secret (only known to Alice). The verification key  $vk$  is known to everyone. And  $sk \neq vk$

Examples: RSA based, ElGamal based, Schnorr, ...

# Hashes

- ▶ hash algorithm  $H : \mathcal{M} \rightarrow \mathcal{D}$



- ▶ **preimage resistant:** given a digest  $d$ , it is computationally infeasible to find any message  $m$  such that  $H(m) = d$
- ▶ **collision resistance:** it is hard to find two different messages  $m_1 \neq m_2$  such that  $H(m_1) = H(m_2)$
- ▶ applications: commitment schemes, signature schemes, MACs, key derivation algorithms, ...

Examples: MD5, SHA-1, ...



# Many more crypto primitives

- ▶ Message Authentication Codes (MACs)
- ▶ Zero Knowledge Proofs (ZKPs)
- ▶ Fully Homomorphic Encryption (FHE)
- ▶ ...

# Cryptographic protocols

**More complex systems needed!**

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$$\frac{e = E(K, \text{Transfer 100 € on Amazon's account})}{h = H(E(K, \text{Transfer 100 € on Amazon's account}))} \rightarrow$$



# More complex systems needed!



$$\begin{array}{l} e = E(K, \text{Transfer 100 € on Amazon's account}) \\ \hline h = H(E(K, \text{Transfer 100 € on Amazon's account})) \end{array} \rightarrow$$



## Replay attack



$$\xrightarrow{(e,h)}$$



$$\begin{array}{l} \xrightarrow{(e,h)} \\ \vdots \\ \xrightarrow{(e,h)} \end{array}$$



# Cryptographic protocols

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Programs relying on **cryptographic primitives** and whose goal is the establishment of “secure” communications.

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Programs relying on **cryptographic primitives** and whose goal is the establishment of “secure” communications.

## But!

Many exploitable errors are due not to design errors in the primitives, but to the way they are used, *i.e.* bad protocol design and buggy or not careful enough implementation

## Numerous deployed protocols are flawed!!!

**Needham-Schroeder protocol** - G. Lowe, "An attack on the Needham-Schroeder public-key authentication protocol"

**Kerberos protocol** - I. Cervesato, A. D. Jaggard, A. Scedrov, J. Tsay, and C. Walstad, "Breaking and fixing public-key kerberos"

**Single-Sign-On protocol** - A. Armando, R. Carbone, L. Compagna, J. Cuellar, and M. L. Tobarra, "Formal analysis of SAML 2.0 web browser single sign-on: breaking the SAML-based single sign-on for google apps"

**PKCS#11 API** - M. Bortolozzo, M. Centenaro, R. Focardi, and G. Steel, "Attacking and fixing PKCS#11 security tokens"

**BAC protocol** - T. Chothia, and V. Smirnov, "A traceability attack against e-passports"

**AKA protocol** - M. Arapinis, L. Mancini, E. Ritter, and M. Ryan, "New privacy issues in mobile telephony: fix and verification"

...



## Important remarks

- ▶ **Cryptographic algorithms and protocols should be public!**
  - Do not use any proprietary crypto primitive or protocol

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- ▶ **Cryptographic algorithms and protocols should be public!**
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- ▶ **Cryptographic protocols are not the solution to every security problem!**
  - Social engineering attacks
  - Software bugs
  - ...

# Outline of the course (Weeks 1-5)

- ▶ Symmetric ciphers
  - ▶ Historical ciphers
  - ▶ Stream ciphers
  - ▶ Block ciphers
  
- ▶ Message integrity and Collision resistance
  
- ▶ Asymmetric ciphers
  
- ▶ Cryptographic protocols

# Historical ciphers

# Rail fence cipher

- ▶ shared secret key  $k \in \mathbb{N}$
- ▶ Encryption: plaintext written in columns of size  $k$ . The ciphertext is the concatenation of the resulting rows.

$k=6$

$m =$  THIS COURSE AIMS TO INTRODUCE YOU TO THE PRINCIPLES AND TECHNIQUES OF SECURING COMPUTERS

T	O	A	O	O	Y		R	L	D	N		C		T
H	U	I		D	O	T	I	E		I	O	U	C	E
I	R	M	I	U	U	H	N	S	T	Q	F	R	O	R
S	S	S	N	C		E	C		E	U		I	M	S
C		E	T	E	T		I	A	C	E	S	N	P	
		T	R		O	P	P	N	H	S	E	G	U	Q

$c =$  TOA00Y RLDN C THUI DOTIE IOUCEIRMIUHNSTQFRORSSSSNC EC EU IMS E TET IACESNPC TR OPPNHSEGUQ

- ▶ Decryption: ciphertext written in rows of size  $\frac{|c|}{k}$

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T	O	A	O	O	Y		R	L	D	N		C		T
H	U	I		D	O	T	I	E		I	O	U	C	E
I	R	M	I	U	U	H	N	S	T	Q	F	R	O	R
S	S	S	N	C		E	C		E	U		I	M	S
C		E	T	E	T		I	A	C	E	S	N	P	
		T	R		O	P	P	N	H	S	E	G	U	Q

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- ▶ Decryption: ciphertext written in rows of size  $\frac{|c|}{k}$

But small key space size:  $k < |c| \Rightarrow$  brute force attack!!

# Substitution cipher

- ▶ shared secret: a permutation  $\varpi$  of the set of characters

$\varpi =$  *a ↦ q b ↦ w c ↦ e d ↦ r e ↦ t f ↦ y g ↦ u h ↦ i i ↦ o j ↦ m k ↦ a l ↦ s*  
*m ↦ d n ↦ f o ↦ g p ↦ h q ↦ j r ↦ k s ↦ l t ↦ z u ↦ x v ↦ c w ↦ v x ↦ b*  
*y ↦ n z ↦ p*

- ▶ Encryption: apply  $\varpi$  to each character of the plaintext.

$$E(\varpi, m_1 \dots m_n) = \varpi(m_1) \dots \varpi(m_n)$$

- ▶ Decryption: apply  $\varpi^{-1}$  to each character of the plaintext.

$$D(\varpi, c_1 \dots c_n) = \varpi^{-1}(c_1) \dots \varpi^{-1}(c_n)$$

# Substitution cipher: example

- m = THIS COURSE AIMS TO INTRODUCE YOU TO THE PRINCIPLES AND TECHNIQUES OF SECURING COMPUTERS AND COMPUTER NETWORKS WITH FOCUS ON INTERNET SECURITY. THE COURSE IS EFFECTIVELY SPLIT INTO TWO PARTS. FIRST INTRODUCING THE THEORY OF CRYPTOGRAPHY INCLUDING HOW MANY CLASSICAL AND POPULAR ALGORITHMS WORK E.G. DES, RSA, DIGITAL SIGNATURES, AND SECOND PROVIDING DETAILS OF REAL INTERNET SECURITY PROTOCOLS, ALGORITHMS, AND THREATS, E.G. IPSEC, VIRUSES, FIREWALLS. HENCE, YOU WILL LEARN BOTH THEORETICAL ASPECTS OF COMPUTER AND NETWORK SECURITY AS WELL AS HOW THAT THEORY IS APPLIED IN THE INTERNET. THIS KNOWLEDGE WILL HELP YOU IN DESIGNING AND DEVELOPING SECURE APPLICATIONS AND NETWORK PROTOCOLS AS WELL AS BUILDING SECURE NETWORKS.
- c = ZIOL EGXKLT QODL ZG OFZKGRXET NGX ZG ZIT HKOFEOHSTL QFR ZTEIFOJXTL GY LTEXKOFU EGDHXZTKL QFR EGDHXZTK FTZVGKAL VOZI YGEXL GF OFZTKFTZ LTEXKOZN. ZIT EGXKLT OL TYYTEZOCTSN LHSOZ OFZG ZVG HQKZL. YOKLZ OFZKGRXEUFU ZIT ZITGKN GY EKNHZGUKQHIN OFESXROFU IGV DQFN ESQLOEQS QFR HGHSQK QSUGKOZIDL VGKA T.U. RTL, KLQ, ROUOZQS LOUFQZXKTL, QFR LTEGFR HKGCOROFU RTZQOSL GY KTQS OFZTKFTZ LTEXKOZN HKGZGEGSL, QSUGKOZIDL, QFR ZIKTQZL, T.U. OHLTE, COKXLTL, YOKTVQSSL. ITFET, NGX VOSS STQKF WGZI ZITGKTZOEQS QLHTEZL GY EGDHXZTK QFR FTZVGKA LTEXKOZN QL VTSS QL IGV ZIQZ ZITGKN OL QHHSOTR OF ZIT OFZTKFTZ. ZIOL AFGVSTRUT VOSS ITSH NGX OF RTLOUFOFU QFR RTCTSGHOFU LTEXKT QHHSOEQZOGFL QFR FTZVGKA HKGZGEGSL QL VTSS QL WXOSROFU LTEXKT FTZVGKAL.



# Breaking the substitution cipher

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- ▶ Key space size:  $|\mathcal{K}| = 26! (\approx 2^{88}) \Rightarrow$  brute force infeasible!

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- ▶ Key space size:  $|\mathcal{K}| = 26! (\approx 2^{88}) \Rightarrow$  brute force infeasible!
- ▶ Exploit regularities of the language
  - ▶ Use frequency of letters in english text  
 $e > t > a > o$
  - ▶ Use frequency of digrams in english text  
 $th > he > in > er$
  - ▶ Use frequency of trigrams in english text  
 $the > and > x ing$
  - ▶ Use expected words

# Breaking the substitution cipher: example

c = ZIOL EGXKLT QODL ZG OFZKGRXET NGX ZG ZIT HKOFEOHSTL QFR ZTEIFOJXTL GY  
LTEXKOFU EGDHXZTKL QFR EGDHXZTK FTZVGKAL VOZI YGEXL GF OFZTKFTZ  
LTEXKOZN. ZIT EGXKLT OL TYYTEZOCTSN LHSOZ OFZG ZVG HQKZL. YOKLZ  
OFZKGRXEUFU ZIT ZITGKN GY EKNHZGUKQHIN OFESXROFU IGV DQFN ESQLOEQS  
QFR HGHSQK QSUGKOZIDL VGKA T.U. RTL, KLQ, ROUOZQS LOUFQZXKTL, QFR  
LTEGFR HKGCROROFU RTZQOSL GY KTQS OFZTKFTZ LTEXKOZN HKGZGEGSL,  
QSUGKOZIDL, QFR ZIKTQZL, T.U. OHLTE, COKXLTL, YOKTVQSSL. ITFET, NGX  
VOSS STQKF WGZI ZITGKTZOEQS QLHTEZL GY EGDHXZTK QFR FTZVGKA  
LTEXKOZN QL VTSS QL IGV ZIQZ ZITGKN OL QHHSOTR OF ZIT OFZTKFTZ. ZIOL  
AFGVSTRUT VOSS ITSH NGX OF RTLOUFOFU QFR RTCTSGHOFU LTEXKT  
QHHSOEQZOGFL QFR FTZVGKA HKGZGEGSL QL VTSS QL WXOSROFU LTEXKT  
FTZVGKAL.

# Breaking the substitution cipher: example

c = TIOL EGXKLE QODL TG OFTKGRXEE NGX TG TIE HKOFEOHSEL QFR TEEIFOJXEL GY  
LEEXKOFU EGDHXTEKL QFR EGDHXTEK FETVGKAL VOTI YGEXL GF OFTEKFET  
LEEXKOTN. TIE EGXKLE OL EYYEETOCESN LHSOT OFTG TVG HQKTL. YOKLT  
OFTKGRXEOFU TIE TIEGKN GY EKNHTGUKQHIN OFESXROFU IGV DQFN ESQLOEQS  
QFR HGHSQK QSUGKOTIDL VGKA E.U. REL, KLQ, ROUOTQS LOUFQTXKEL, QFR  
LEEGFR HKGCFOROFU RETQOSL GY KEQS OFTEKFET LEEXKOTN HKGTGEGSL,  
QSUGKOTIDL, QFR TIKEQTL, E.U. OHLEE, COKXLEL, YOKEVQSSL. IEFEE, NGX  
VOSS SEQKF WGTI TIEGKETOEQS QLHEETL GY EGDHXTEK QFR FETVGKA  
LEEXKOTN QL VESS QL IGV TIQT TIEGKN OL QHHSOER OF TIE OFTEKFET. TIOL  
AFGVSERUE VOSS IESH NGX OF RELOUFOFU QFR RECESGHOFU LEEXKE  
QHHSOEQTOTGFL QFR FETVGKA HKGTGEGSL QL VESS QL WXOSROFU LEEXKE  
FETVGKAL.

Most common letters in c: t > z > ...

# Breaking the substitution cipher: example

c = THOL EGXKLE QODL TG OFTKGRXEE NGX TG THE HKOFEOHSEL QFR TEEHFOJXEL GY  
LEEXKOFU EGDHXTEKL QFR EGDHXTEK FETVGKAL VOTH YGEXL GF OFTEKFET  
LEEXKOTN. THE EGXKLE OL EYYEETOESN LHSOT OFTG TVG HQKTL. YOKLT  
OFTKGRXEUFU THE THEGKN GY EKNHTGUKQHIN OFESXROFU HGV DQFN ESQLOEQS  
QFR HGHSQK QSUGKOTHDL VGKA E.U. REL, KLQ, ROUOTQS LOUFQTXKEL, QFR  
LEEGFR HKGCOROFU RETQOSL GY KEQS OFTEKFET LEEXKOTN HKGTGEGSL,  
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VOSS SEQKF WGTH THEGKETOEQS QLHEETL GY EGDHXTEK QFR FETVGKA  
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AFGVSERUE VOSS HESH NGX OF RELOUFOFU QFR RECESGHOFU LEEXKE  
QHHSOEQTGFL QFR FETVGKA HKGTGEGSL QL VESS QL WXOSROFU LEEXKE  
FETVGKAL.

Most common digrams in c: of > zi > ...

t<sub>1</sub>→z suggests h<sub>1</sub>→i

# Breaking the substitution cipher: example

c = THIL EGXKLE QIDL TG INTKGRXEE NGX TG THE HKINEIHSEL QNR TEEHNIJXEL GY  
LEEXKINU EGDHXTEKL QNR EGDHXTEK NETVGKAL VITH YGEXL GN INTEKNET  
LEEXKITN. THE EGXKLE IL EYYEETICESN LHSIT INTG TVG HQKTL. YIKLT  
INTKGRXEINU THE THEGKN GY EKNHTGUKQHNN INESXRINU HGV DQNN ESQLLIEQS  
QNR HGHXSQK QSUGKITHDL VGKA E.U. REL, KLQ, RIUITQS LIUNQTXKEL, QNR  
LEEGNR HKGCIRINU RETQISL GY KEQS INTEKNET LEEXKITN HKGTGEGSL,  
QSUGKITHDL, QNR THKEQTL, E.U. IHLEE, CIKXLEL, YIKEVQSSL. HENEE, NGX  
VISS SEQKN WGTH THEGKETIEQS QLHEETL GY EGDHXTEK QNR NETVGKA  
LEEXKITN QL VESS QL HGV THQT THEGKN IL QHHSIER IN THE INTEKNET. THIL  
ANGVSERUE VISS HESH NGX IN RELIUNINU QNR RECESGHINU LEEXKE  
QHHSIEQTIGNL QNR NETVGKA HKGTGEGSL QL VESS QL WXISRINU LEEXKE  
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Most common digrams in c: of > zi > ...

we guess in  $\mapsto$  of

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NETVGKAL.

We identify in c the word INTEKNET  
suggests  $r_i \rightarrow k$



# Breaking the substitution cipher: example

c = THIS EGXRSE QIDS TG INTRGRXEE NGX TG THE HRINEIHSES QNR TEEHNIJXES GY  
SEEXRINU EGDHXTERS QNR EGDHXTER NETVGRAS VITH YGEXS GN INTERNET  
SEEXRITN. THE EGXRSE IS EYYEETICESN SHSIT INTG TVG HQRTS. YIRST  
INTRGRXEINU THE THEGRN GY ERNHTGURQHHN INESXRINU HGV DQNN ESQSSIEQS  
QNR HGHXSQR QSUGRITHDS VGRA E.U. RES, RSQ, RIUITQS SIUNQTXRES, QNR  
SEEGNR HRGCIRINU RETQISS GY REQS INTERNET SEEXRITN HRGTGEGSS,  
QSUGRITHDS, QNR THREQTS, E.U. IHSEE, CIRXSES, YIREVQSSS. HENEE, NGX  
VISS SEQRN WGTH THEGRETEIQS QSHEETS GY EGDHXTER QNR NETVGRA  
SEEXRITN QS VESS QS HGV THQT THEGRN IS QHHSIER IN THE INTERNET. THIS  
ANGVSERUE VISS HESH NGX IN RESIUNINU QNR RECESGHINU SEEXRE  
QHHSIEQTIGNS QNR NETVGRA HRGTGEGSS QS VESS QS WXISRINU SEEXRE  
NETVGRAS.

The first word is THIL  
suggests  $s \rightarrow l$

# Breaking the substitution cipher: example

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Going back to letter frequency and a few more guesses!!

# Vigenere cipher

- ▶ shared secret key: a word  $w$  over the english alphabet

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- ▶ shared secret key: a word  $w$  over the english alphabet
- ▶ Encryption: break the plaintext  $m = m_1 \dots m_n$  in  $\frac{|m|}{|w|}$  blocks, and encrypt each block as follows

$$\begin{array}{rcccc} & m_{i+1} & & \dots & m_{i+|w|} \\ + & w_1 & & \dots & w_{|w|} \\ \hline & \underbrace{m_{i+1} + w_1}_{c_{i+1}} \pmod{26} & & \dots & \underbrace{m_{i+|w|} + w_{|w|}}_{c_{i+|w|}} \pmod{26} \end{array}$$

Concatenate the resulting blocks to obtain the ciphertext

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$$\begin{array}{r} m_{i+1} \qquad \dots \qquad m_{i+|w|} \\ + \quad w_1 \qquad \dots \qquad w_{|w|} \\ \hline \underbrace{m_{i+1} + w_1 \pmod{26}}_{c_{i+1}} \quad \dots \quad \underbrace{m_{i+|w|} + w_{|w|} \pmod{26}}_{c_{i+|w|}} \end{array}$$

Concatenate the resulting blocks to obtain the ciphertext

- ▶ Decryption: break the ciphertext  $c = c_1 \dots c_n$  in  $\frac{|m|}{|w|}$  blocks, and decrypt each block as follows

$$\begin{array}{r} c_{i+1} \qquad \dots \qquad c_{i+|w|} \\ - \quad w_1 \qquad \dots \qquad w_{|w|} \\ \hline \underbrace{c_{i+1} - w_1 \pmod{26}}_{m_{i+1}} \quad \dots \quad \underbrace{c_{i+|w|} - w_{|w|} \pmod{26}}_{m_{i+|w|}} \end{array}$$

Concatenate the resulting blocks to retrieve the message

# Vigenere cipher: example

$w = \text{MACBETH}$

$m = \text{WHEN SHALL WE THREE MEET AGAIN IN THUNDERLIGHTNING OR IN RAIN}$

	M	A	C	B	E	T	H	M	A	C	B	E	T	H	...	M	A
+	W	H	E	N	S	H	A	L	L	W	E	T	H	R	...	I	N
<hr/>																	
	J	I	H	P	X	B	I	Y	M	Z	G	Y	B	Z	...	V	O

$c = \text{IHGO WAHXL YF XAYQE OFIM HSAKO MG ATUPEIKSUGJVRBUS OT JR KHUN}$

# Breaking the Vigenere cipher

# Breaking the Vigenere cipher

- ▶ Suppose we know the length of the key  $w$ . Break the ciphertext in  $\frac{|c|}{|w|}$  blocks:

$$c_1 \dots c_{|w|} \parallel c_{|w|+1} \dots c_{2|w|} \parallel \dots \parallel c_{|c|-|w|+1} \dots c_{|c|}$$

for each position in  $\{1, \dots, |w|\}$ , consider the characters  $c_{j|w|+i}$  for all  $j \in \frac{|c|}{|w|}$ . All these characters have been encrypted using the same key character  $w_i$ . Perform letter frequency analysis on this set of characters.



# Breaking the Vigenere cipher

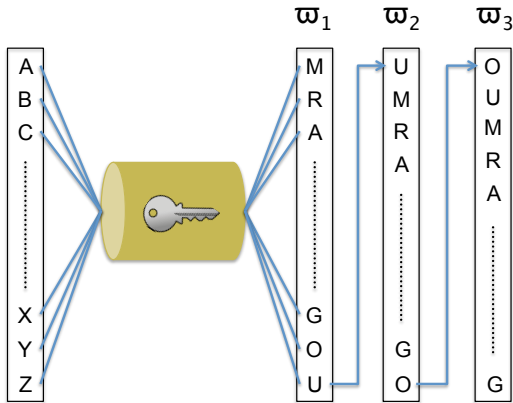
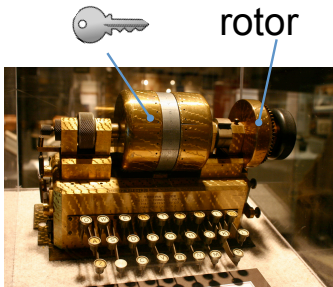
- ▶ Suppose we know the length of the key  $w$ . Break the ciphertext in  $\frac{|c|}{|w|}$  blocks:

$$c_1 \dots c_{|w|} \parallel c_{|w|+1} \dots c_{2|w|} \parallel \dots \parallel c_{|c|-|w|+1} \dots c_{|c|}$$

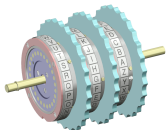
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- ▶ If the size of  $w$  is not known apply Kasiski's method to narrow the possibilities:
  - ▶ identify all the sequences of letters of length greater than 4 that occur more than once
  - ▶ for each such sequence compute the distance between two of its occurrences
  - ▶ compute the corresponding possible key-length

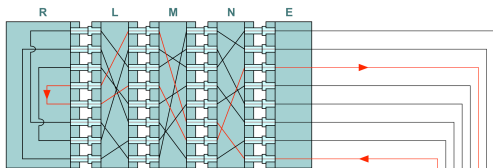
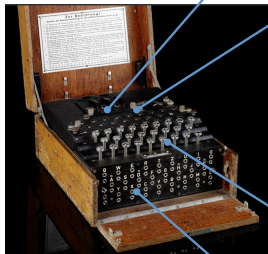
# Rotor machines: the Herbern machine



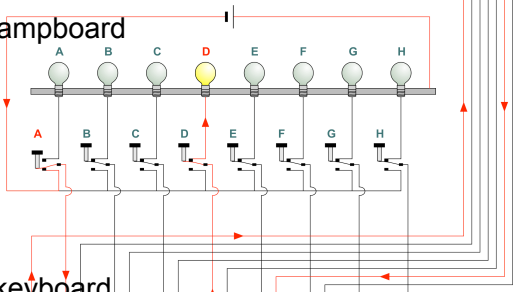
# Rotor machines: the enigma machine



Rotors



lampboard



keyboard

plugboard

