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25 September 2011
Near the end of his life, one of the Twentieth Century’s most eminent mathematicians wrote in his memoir:
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There is one comforting conclusion which is easy for a real mathematician. Real mathematics has no effects on war. No one has yet discovered any warlike purpose to be served by the theory of numbers or relativity, and it seems very unlikely that anyone will do so for many years.

G. H. Hardy, *A Mathematician’s Apology*, p. 140 (1940)
The value of basic science...
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He was wrong!
Albert Einstein’s Special Theory of Relativity (1905), with its famous equation, $E = mc^2$, relates energy, mass, and the speed of light ($c = 299 792 458$ m/s (exact!) $\approx 186 282$ miles/s in vacuum).
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Otto Hahn and Fritz Strassman in Germany first split the uranium atom by neutron bombardment in 1938. This was confirmed by Lise Meitner and Otto Frisch (Meitner’s nephew) in Sweden on December 24, 1938.
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Relativity and quantum mechanics . . .

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- Japan surrendered August 14, 1945 (formally on September 2), ending World War II.
- Nuclear arms race and the Cold War began shortly thereafter.
Whitfield Diffie and Martin Hellman at Stanford University in 1976, and Ralph Merkle at the University of California, Berkeley in 1975 (but unpublished until 1978), independently discovered public-key cryptography. Their work was based on some fundamental problems of number theory, and unleashed a flurry of research:

![Cryptographic publication counts](image)

This lecture will discuss why this work matters to every citizen.
In September 2005, a paper appeared in the *Journal of Cryptology* on relativistic cryptography, and a Web search with http://www.google.com/ found 17 documents (39 in September 2011) with that phrase, the oldest being from 1998. One has the title *Remarks on Mistrustful Quantum and Relativistic Cryptography*, connecting the three basic fields in the introduction to this talk.
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Corrections from both Special Relativity (1905) and General Relativity (1916) are essential for the Global Positioning System on which modern air traffic now depends.
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**cipher** A message written in a secret code.
**Preliminaries: Some dictionary definitions**

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**plaintext**  The unencrypted form of an encrypted message.

**ciphertext**  A text in encrypted form, as opposed to the plain text.
**prime number**  A positive whole number not divisible without a remainder by any positive whole number other than itself and one.

For example, the primes up to 100 are:

<p>| | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>5</td>
<td>7</td>
<td>11</td>
<td>13</td>
<td>17</td>
<td>19</td>
<td>23</td>
<td>29</td>
<td>31</td>
<td>37</td>
<td>41</td>
</tr>
<tr>
<td>43</td>
<td>47</td>
<td>53</td>
<td>59</td>
<td>61</td>
<td>67</td>
<td>71</td>
<td>73</td>
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<td>83</td>
<td>89</td>
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<tr>
<td>43</td>
<td>47</td>
<td>53</td>
<td>59</td>
<td>61</td>
<td>67</td>
<td>71</td>
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<td>79</td>
<td>83</td>
<td>89</td>
<td>97</td>
<td></td>
</tr>
</tbody>
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**steganography**  Hiding a secret message within a larger object in such a way that others can not discern the presence or contents of the hidden message.

For example, a message might be hidden within an image by changing the least significant bits to be the message bits.
A cartoonist’s view of prime numbers

WHO CAN TELL ME WHAT A "PRIME NUMBER" IS?

ONE WHERE A HOT BABE WITH A SULTRY VOICE ANSWERS THE PHONE.

OH, WHAT-THE-HECK! THANK GOD FOR TENURE.

SKOOL

TEE HEE TEE HEE

© 2005 CREATORS SYNDICATE, INC. www.creators.com

2+2=6

KAT

10-7
Simple cryptography: substitution ciphers

Change each letter into another unique letter.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q</td>
<td>U</td>
<td>Z</td>
<td>M</td>
<td>X</td>
<td>L</td>
<td>K</td>
<td>T</td>
<td>G</td>
<td>P</td>
<td>R</td>
<td>H</td>
<td>O</td>
</tr>
<tr>
<td>N</td>
<td>O</td>
<td>P</td>
<td>Q</td>
<td>R</td>
<td>S</td>
<td>T</td>
<td>U</td>
<td>V</td>
<td>W</td>
<td>X</td>
<td>Y</td>
<td>Z</td>
</tr>
<tr>
<td>V</td>
<td>Y</td>
<td>D</td>
<td>E</td>
<td>W</td>
<td>J</td>
<td>S</td>
<td>A</td>
<td>N</td>
<td>C</td>
<td>F</td>
<td>I</td>
<td>B</td>
</tr>
</tbody>
</table>

For example, to encrypt a message, use the rules in that table like this:

<table>
<thead>
<tr>
<th>plaintext</th>
<th>ATTACK</th>
<th>AT</th>
<th>DAWN</th>
</tr>
</thead>
<tbody>
<tr>
<td>substitute</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>ciphertext</td>
<td>QSSQZR</td>
<td>QS</td>
<td>MQCV</td>
</tr>
</tbody>
</table>

To decrypt, just reverse the substitution direction:

<table>
<thead>
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<th>QSSQZR</th>
<th>QS</th>
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</tr>
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<td>↓</td>
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<td>DAWN</td>
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</table>
One of the earliest substitution ciphers is the **Caesar cipher** (ca. 50BCE). The substitutions are not to randomly-ordered letters, but rather to the same alphabet shifted circularly by three places.

```
A B C D E F G H I J K L M
↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓
D E F G H I J K L M N O P
↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓
N O P Q R S T U V W X Y Z
```

Encryption proceeds as before:

```
plaintext  ATTACK  AT  DAWN
```

```
substitute  ↓↓↓↓↓↓↓↓↓↓↓↓↓
```

```
ciphertext  DWWDFN  DW  GDZQ
```

Decryption is just the reverse: change ↓ to ↑.
There are two important features of substitution ciphers:

- A **secret key** controls the encryption, either the substitution table (for example, \text{QUZMXLKTGPRHOVYDEWJSANCFIB}), or for the simpler Caesar cipher, just the number \text{3} that determines the table shift distance.
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- Encryption and decryption are **symmetric**: the same key is used for both. Most cryptographic methods share this property (but public-key cryptography does not).
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6. Given the circumstances that command its application, the system must be easy to use, requiring neither mental strain nor the knowledge of a long series of rules to observe.
We have to assume that an attacker has captured our ciphertext. Encryption security then depends primarily on:

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- the difficulty of cracking captured ciphertext by cryptanalysis.
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- using multiple levels and/or methods of encryption, and
- changing the key at suitable intervals (daily, hourly, or even with each message).
Expected letter frequencies of natural-language text is important for cryptanalysis. Large bodies of English text suggest the order `etanoshrdlu`:

<table>
<thead>
<tr>
<th>Alice in Wonderland</th>
<th>Hamlet</th>
<th>Roget's Thesaurus</th>
<th>Treasure Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.75% space</td>
<td>15.70% space</td>
<td>16.00% space</td>
<td>18.61% space</td>
</tr>
<tr>
<td>9.40% e</td>
<td>9.04% e</td>
<td>8.41% e</td>
<td>9.28% e</td>
</tr>
<tr>
<td>7.43% t</td>
<td>7.11% t</td>
<td>5.81% a</td>
<td>6.96% t</td>
</tr>
<tr>
<td>6.00% a</td>
<td>6.53% o</td>
<td>5.63% t</td>
<td>6.54% a</td>
</tr>
<tr>
<td>5.69% o</td>
<td>5.87% a</td>
<td>5.49% i</td>
<td>6.03% o</td>
</tr>
<tr>
<td>5.22% i</td>
<td>5.09% i</td>
<td>5.34% n</td>
<td>5.31% n</td>
</tr>
<tr>
<td>4.92% h</td>
<td>4.95% s</td>
<td>5.27% o</td>
<td>4.95% h</td>
</tr>
<tr>
<td>4.84% n</td>
<td>4.92% h</td>
<td>4.87% r</td>
<td>4.95% i</td>
</tr>
<tr>
<td>4.46% s</td>
<td>4.90% n</td>
<td>4.36% s</td>
<td>4.67% s</td>
</tr>
<tr>
<td>3.86% r</td>
<td>4.63% r</td>
<td>3.84% ,</td>
<td>4.26% r</td>
</tr>
<tr>
<td>3.36% d</td>
<td>3.71% l</td>
<td>3.41% c</td>
<td>3.77% d</td>
</tr>
<tr>
<td>3.24% l</td>
<td>3.06% d</td>
<td>3.33% l</td>
<td>3.19% l</td>
</tr>
<tr>
<td>2.40% u</td>
<td>2.70% u</td>
<td>2.65% u</td>
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US and Britain monitor and analyze all transatlantic telephone and network traffic.
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- **Key reuse makes cryptanalysis easier.**
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- Unless the key is changed, a given plaintext letter is always converted to the same ciphertext letter, facilitating frequency-analysis attacks.
- Key reuse makes cryptanalysis easier.
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- Eavesdropping is rarely detectable (photons and electrons cannot be tagged).
- Traffic analysis can still reveal important information, even if the traffic itself cannot be understood by the attacker.
Stream and block ciphers

- Simple encryption methods work on a character (or bit) at a time; they are **stream ciphers**.

  In stream ciphers, a particular character is encrypted identically, no matter where it appears in the data stream. A transmission error in a single character affects only that character.

- Better methods work on groups of characters (or bits) at a time; they are **block ciphers**.

  In a block cipher, the encryption of a particular character depends on all others in the same block. Thus, in a block method, a particular character will usually be encrypted differently, depending on its surroundings. A transmission error in a single character affects the entire block.

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- **The best modern encryption methods are usually block ciphers.**
Cryptanalysis is possible whenever there are patterns in the encryption of plaintext to ciphertext. The only way to prevent cryptanalysis is to use a different encryption for each plaintext letter, because that destroys all patterns.

A **one-time pad** satisfies this requirement. For example, use successive letters of text from a mutually-agreed-on book (the **key**) to determine the shift count of a Caesar-like substitution cipher:

```
Call me Ishmael. Some years ago—never mind how long precisely—having little or no money in my purse, and nothing particular to interest me on shore, I thought I would sail about a little and see the watery part of the world.
```

Herman Melville, *Moby Dick*, London (1851)
Weaknesses of our one-time pad

Unfortunately, when a book of natural-language text provides the one-time pad, there are still patterns present that can allow cryptanalysis (e.g., and, I, little, me, and the occur twice, and some words have repeated letters (ee, ll, and tt)).
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- What is needed is a **completely-random string of letters** of **unlimited length** for the one-time pad.

- A computer method for generating random numbers requires a starting number, called the seed, that serves as the encryption key.
Example of the one-time pad

The encryption does not reveal message length, although it **does** reveal common plaintext prefixes:

```plaintext
crypt(123,"A")
    2b 04aa0f ef15ce59 654a0dc6 ba409618 daef6924 5729580b af3af319 f579b0bc
crypt(123,"AB")
   2b47 315b 22fdc9f1 b90d4fdb 1eb8302a 4944eddb e7dd1bff 8d0d1f10 1e46b93c
crypt(123,"ABC")
   2b4775 2c 286a4724 40bf188f c08caffa 1007d4cc 2c2495f9 cd999566 abfe0c2d
crypt(123,"ABCD")
   2b477571 f970b4a2 7346ca58 742e8379 e0ce97b3 1d69dc73 c7d921dc 018bc480
```
Example of the one-time pad

The encryption does not reveal message length, although it **does** reveal common plaintext prefixes:

encrypt(123,"A")

```
2b 04aa0f ef15ce59 654a0dc6 ba409618 daef6924 5729580b
af3af319 f579b0bc
```

encrypt(123,"AB")

```
2b47 315b 22fdcf9f1 b90d4fdb 1eb8302a 4944eddb e7dd1bff
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```
Example of the one-time pad . . .

The encryption does not reveal letter repetitions:

```python
encrypt(123, "AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA"
  2b46736e 3b83cd28 777d88c8 ad1b12dc c28010ef 407d3513
e1ed75bc 5737fd71 6e68fb7d 4ac31248 94f21f9f d009455f
6d299f
```

Now encrypt a famous message from American revolutionary history:

```python
ciphertext = encrypt(123, "One if by land, two if by sea: Paul Revere's Ride, 16 April 1775")
println ciphertext
```

```plaintext
3973974d 63a8ac49 af5cb3e8 da3efdbb f5b63ece 68a21434
19cca7e0 7730dc80 8e9c265c 5be7476c c51605d1 af1a6d82
9114c057 620da15b 0670bb1d 3c95c30b ed
```
The encryption does not reveal letter repetitions:

```
e_encrypt(123,"AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA")
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```
Example of the one-time pad...

Attempt to decrypt the ciphertext with a nearby key. Decryption does reveal the message length, although that flaw could easily be fixed:

\[
\text{decrypt}(122, \text{ciphertext})
\]

\[
?^\wedge/?)?D?fN&????w??V???Gj5??????(????1????J???i?i)y?I?-G??????b?o??X?
\]
Example of the one-time pad ...

Attempt to decrypt the ciphertext with a nearby key. Decryption *does* reveal the message length, although that flaw could easily be fixed:

```
decrypt(122, ciphertext)
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Attempt to decrypt the ciphertext with the correct key:

```
decrypt(123, ciphertext)
```

*One if by land, two if by sea: Paul Revere’s Ride, 16 April 1775*
Example of the one-time pad ...

Attempt to decrypt the ciphertext with a nearby key. Decryption \textbf{does} reveal the message length, although that flaw could easily be fixed:

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\end{verbatim}

Attempt to decrypt the ciphertext with the correct key:

\begin{verbatim}
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\end{verbatim}

Attempt to decrypt the ciphertext with another nearby key:

\begin{verbatim}
decrypt(124, ciphertext)
\end{verbatim}
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Attempt to decrypt the ciphertext with the correct key:

```
decrypt(123, ciphertext)
```

One if by land, two if by sea: Paul Revere’s Ride, 16 April 1775

Attempt to decrypt the ciphertext with another nearby key:

```
decrypt(124, ciphertext)
```

Lesson: a nearby key is as useless as a faraway key: almost-right isn’t good enough.
Limitations of the one-time pad

• Although very good methods are now known for generating random numbers on a computer, they are always produced by a specific recipe that introduces patterns that can aid cryptanalysis, and most of the popular methods have been cracked.
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- The problem of secure key distribution remains.
Public-key cryptography solves the key-distribution problem. Instead of a single shared secret key, each participant has a pair of keys: a public key, and a companion private key.
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Prime factorization of small numbers is easy:

- $99 = 3 \times 3 \times 11$
- $6860 = 2 \times 2 \times 5 \times 7 \times 7 \times 7$
- $62271 = 3 \times 3 \times 11 \times 17 \times 37$
- $62273 = 62273$ (prime number)
- $97272 = 2 \times 2 \times 2 \times 3 \times 3 \times 7 \times 193$
Public-key cryptography and prime numbers

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\end{align*}
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● Prime factorization of big numbers is hard:

\[
\begin{align*}
1447473570262981491527798 & = 2 \times 109 \times 3687427 \times 12523837 \times 143778289 \\
8992987500442157627511191 & = 19 \times 318023201 \times 1488303778195789 \\
8992987500442157627511193 & = 8992987500442157627511193 \quad \text{prime number} \\
17054727660401396805027270 & = 2082815984930 \times 8188302655539
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Brute-force factorization of an \( N \)-digit number could require trying all factors up to size \( N/2 \) digits: work is \( \mathcal{O}(\sqrt{10^N}) \).
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Security and uses of public-key cryptography

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Examples include secure shell on Unix systems, https://... Web connections, and some recent network protocols.
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Cryptography and the citizen

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- Public-key certification services by large corporations, such as Verisign, are advocated by some, but this just transfers the trust problem to another large organization over which you have no control, and little confidence in. [DigiNotar in July 2011: later bankrupt]
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Registration of public keys in a number of different key servers scattered around the world makes it harder to forge a public key.
Can cryptography ensure privacy?

Alas, no.

Bruce Schneier wrote two editions of a famous book, *Applied Cryptography*, and with Niels Ferguson, co-authored two more, *Practical Cryptography* and *Cryptography Engineering*, describing the mathematics and computer science behind cryptography. He wrote two more books, *Secrets & Lies*, and *Beyond Fear*, that deal with the social aspects of security and privacy.

In modern computer systems, plaintext can be recovered by encryption-key compromise, by capturing data before encryption (e.g., keyboard sniffer, screen images, or keyboard sounds), by trapping data after decryption, or by cracking ciphertext encrypted with weak methods (simple passwords, Bluetooth, WEP on wireless networks, Microsoft Windows passwords and protocols, cell phones, . . . ).
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- Only well-studied publicly-available encryption techniques believed to be secure by the cryptographic research community are trustworthy.
- Beware of "security by obscurity" and "proprietary encryption techniques".

Absence of a published successful attack against an encryption method does not mean that it is secure. Only published reports of repeated failed attacks and mathematical analysis can give confidence in its security.

Storage of encrypted data is perilous: if you forget the key, or an employee leaves with the key, your data is lost, compromised, or could be held hostage.

If an attacker learns your encryption key, your traffic or data may be monitored without your knowledge.
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- If an attacker learns your encryption key, your traffic or data may be monitored without your knowledge.
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- Computer-based facial recognition has high rate of false positives.
Video surveillance cameras in public and corporate areas, and even some homes. And now in cell phones.
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- Cleartext and otherwise unsecured or insecure wireless networks, including cell phones, Bluetooth, garage/car door openers, . . .
- Unicode characters in Internet hostnames (Internationalized Domain Names) can be deceptive.
- Color printer output encoding printer serial number and time stamp.
- Thieves use Bluetooth phones to find Bluetooth-enabled laptops in parked cars, and then steal the laptops.

Reread George Orwell's book *1984*: Big Brother is watching you.
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Legislation in some countries makes use of cryptography a crime or treats cryptography (both research and software) as a weapon subject to prepublication review or export controls, or requires individuals to surrender encryption keys to law enforcement or to a government escrow agency (e.g., the US Clipper Chip proposals of the 1990s).
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A Washington state gubernatorial election, a Mexican Presidential election, and two US Presidential elections, have been statistical ties.
Argonne researchers ’hack’ Diebold e-voting system
Breaking into system using a $10 electronic component was ’ridiculously easy,’ says official at national research lab

September 28, 2011 11:51 AM EST
Computerworld –

Researchers at the Argonne National Laboratory this week showed how an electronic voting machine model that’s expected to be widely used to tally votes in the 2012 elections can be easily hacked using inexpensive, widely-available electronic components.
Conclusions and lessons

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- Oppose database aggregation, and excessive collection of unnecessary data that violates your privacy and your economic security.
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