Cryptography, Freedom, and Democracy

How Basic Science Affects Everyone

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The value of basic science

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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 . . .

He was wrong!

Relativity and quantum mechanics

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- Erwin Schrödinger in Germany discovered the quantum-mechanical wave equation in 1926.
- 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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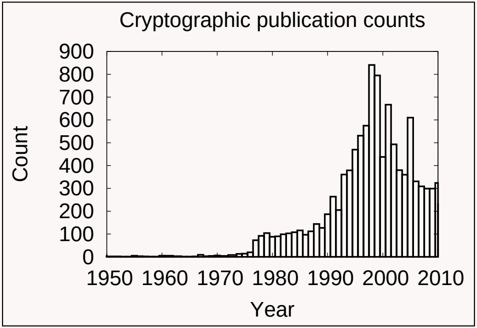
- Nuclear arms race and the Cold War began shortly thereafter.

Number theory

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Martin Hellman at Stanford University in 1976, and Ralph Merkle at the University of California, Berkeley in 1975 (but unpublished until 1978), independently discovered public-key cryptography.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:



This lecture will discuss why this work matters to every citizen.

Unexpected and curious connections

- 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.
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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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ciphertext A text in encrypted form, as opposed to the plain text.

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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:

2 3 5 7 11 13 17 19 23 29 31 37 41

43 47 53 59 61 67 71 73 79 83 89 97

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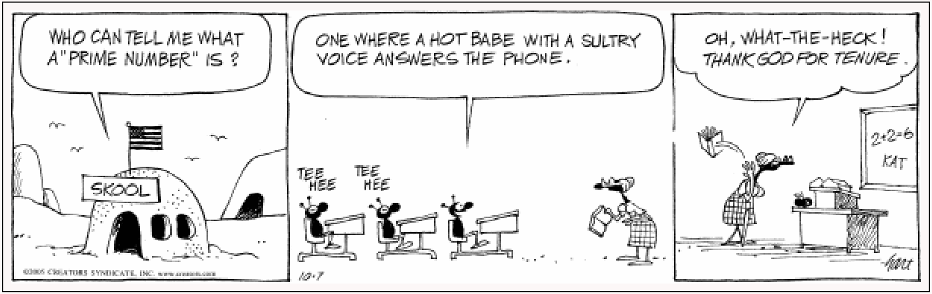
43	47	53	59	61	67	71	73	79	83	89	97	

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



Simple cryptography: substitution ciphers

Change each letter into another unique letter.

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

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

plaintext	**ATTACK**	**AT**	**DAWN**
substitute	↓	↓	↓
ciphertext	**QSSQZR**	**QS**	**MQCV**

To decrypt, just reverse the substitution direction:

ciphertext	**QSSQZR**	**QS**	**MQCV**
substitute	↓	↓	↓
plaintext	**ATTACK**	**AT**	**DAWN**

Simple cryptography: substitution ciphers . . .

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
↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
Q	R	S	T	U	V	W	X	Y	Z	A	B	C

Encryption proceeds as before:

plaintext	**ATTACK**	**AT**	**DAWN**
substitute	↓	↓	↓
ciphertext	**DWWDFN**	**DW**	**GDZQ**

Decryption is just the reverse: change ↓ to ↑.

Cryptographic keys

There are two important features of substitution ciphers:

- A **secret key** controls the encryption, either the substitution table (for example, **QUZMXLKTGPRHOVYDEWJSANCFIB**), or for the simpler Caesar cipher, just the number **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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5. It must be portable, and its usage and function must not require the concourse of several people (consider what happens if you log onto a banking site from computer B when your keys are stored on computer A).
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.

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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).

Frequency analysis

Expected letter frequencies of natural-language text is important for cryptanalysis. Large bodies of English text suggest the order **e t a o i n s h r d l u**:

Alice in Wonderland		Hamlet		Roget's Thesaurus		Treasure Island	
19.75%	space	15.70%	space	16.00%	space	18.61%	space
9.40%	e	9.04%	e	8.41%	e	9.28%	e
7.43%	t	7.11%	t	5.81%	a	6.96%	t
6.00%	a	6.53%	o	5.63%	t	6.54%	a
5.69%	o	5.87%	a	5.49%	i	6.03%	o
5.22%	i	5.09%	i	5.34%	n	5.31%	n
4.92%	h	4.95%	s	5.27%	o	4.95%	h
4.84%	n	4.92%	h	4.87%	r	4.95%	i
4.46%	s	4.90%	n	4.36%	s	4.67%	s
3.86%	r	4.63%	r	3.84%	,	4.26%	r
3.36%	d	3.71%	l	3.41%	c	3.77%	d
3.24%	l	3.06%	d	3.33%	l	3.19%	l
2.40%	u	2.70%	u	2.65%	u	2.28%	u

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- US and Britain monitor and analyze all transatlantic telephone and network traffic.

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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.

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- A transmission error in a single character affects the entire block.

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.
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- Better methods work on groups of characters (or bits) at a time; they are **block ciphers**.
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- Block methods therefore require reliable communications.
- The best modern encryption methods are usually block ciphers.

Uncrackable encryption method: the one-time pad

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:

```
encrypt(123,"A")
        2b 04aa0f ef15ce59 654a0dc6 ba409618 daef6924 5729580b
        af3af319 f579b0bc
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        8d0d1f10 1e46b93c
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        2b47752c 286a4724 40bf188f c08caffa 1007d4cc 2c2495f9
        cd999566 abfe0c2d
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        c7d921dc 018bc480
```

Example of the one-time pad . . .

The encryption does not reveal letter repetitions:

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

Now encrypt a famous message from American revolutionary history:

```
ciphertext = encrypt(123, \
"One if by land, two if by sea: Paul Revere's Ride, 16 April 1775")
println ciphertext
        3973974d 63a8ac49 af5cb3e8 da3efdbb f5b63ece 68a21434
        19cca7e0 7730dc80 8e9c265c 5be7476c c51605d1 af1a6d82
        9114c057 620da15b 0670bb1d 3c95c30b ed
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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:

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decrypt(122, ciphertext)
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Attempt to decrypt the ciphertext with another nearby key:

```
decrypt(124, ciphertext)
??$???W?????N????????!?Z?U???????Q??????3?B}`<?O ?P5%??VdNv??kS??
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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

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- Such problems are sometimes called **one way trap doors**.
- Easy to put needle in haystack, but much harder to remove it.

Public-key cryptography and prime numbers

- Prime factorization of small numbers is easy:

$$\begin{aligned} 99 &= 3 \times 3 \times 11 \\ 6860 &= 2 \times 2 \times 5 \times 7 \times 7 \times 7 \\ 62271 &= 3 \times 3 \times 11 \times 17 \times 37 \\ 62273 &= 62273 \quad \textbf{prime number} \\ 97272 &= 2 \times 2 \times 2 \times 3 \times 3 \times 7 \times 193 \end{aligned}$$

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8992987500442157627511193 &= 8992987500442157627511193 \quad \text{prime number} \\
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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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- Examples include **secure shell** on Unix systems, **https://...** Web connections, and some recent network protocols.

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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.

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- 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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- 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.

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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.

Recent news on e-voting

```
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.
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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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