COS 126

General Computer Science
Fall 2012

Robert Sedgewick

Overview

What is COS 126? Broad, but technical, introduction to computer science.

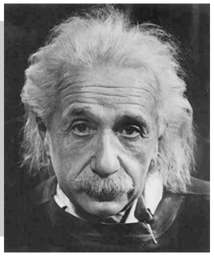
Goals.

- Demystify computer systems.
- Empower you to exploit available technology.
- Build awareness of substantial intellectual underpinnings.

Topics.

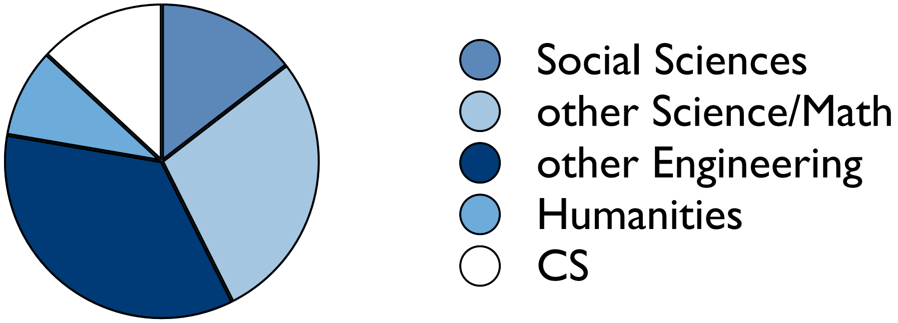
- Programming in Java.
- Machine architecture.
- Theory of computation.
- Applications to science, engineering, and commercial computing.

> *" Computers are incredibly fast, accurate, and stupid; humans are incredibly slow, inaccurate, and brilliant; together they are powerful beyond imagination. "* *– Albert Einstein*

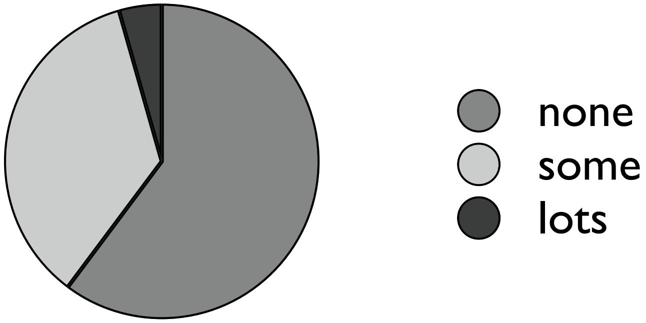


Who are you?

Intended major

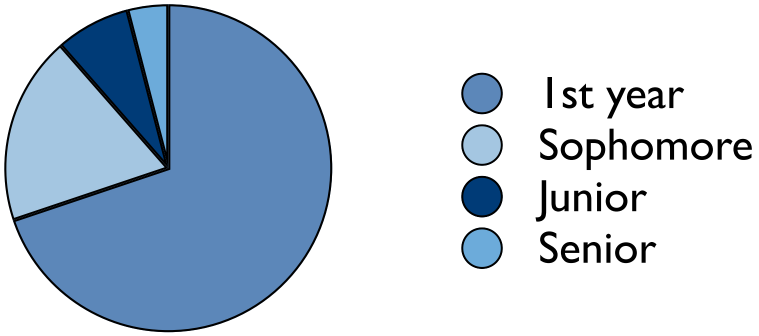


Programming experience



[data from 2011-12]

Class



Over half of all Princeton students take COS 126

The Basics

🟦 Lectures. [Sedgewick]

🟦 RS office hours. ← everyone needs to meet me!

⬛ Precepts. [**Gabai** · **Moretti** · August · Finkelstein · Hadidi · Homilius · Lee· Nadimpalli· Pritchard · Przytycki · Ravi · Wetzel]

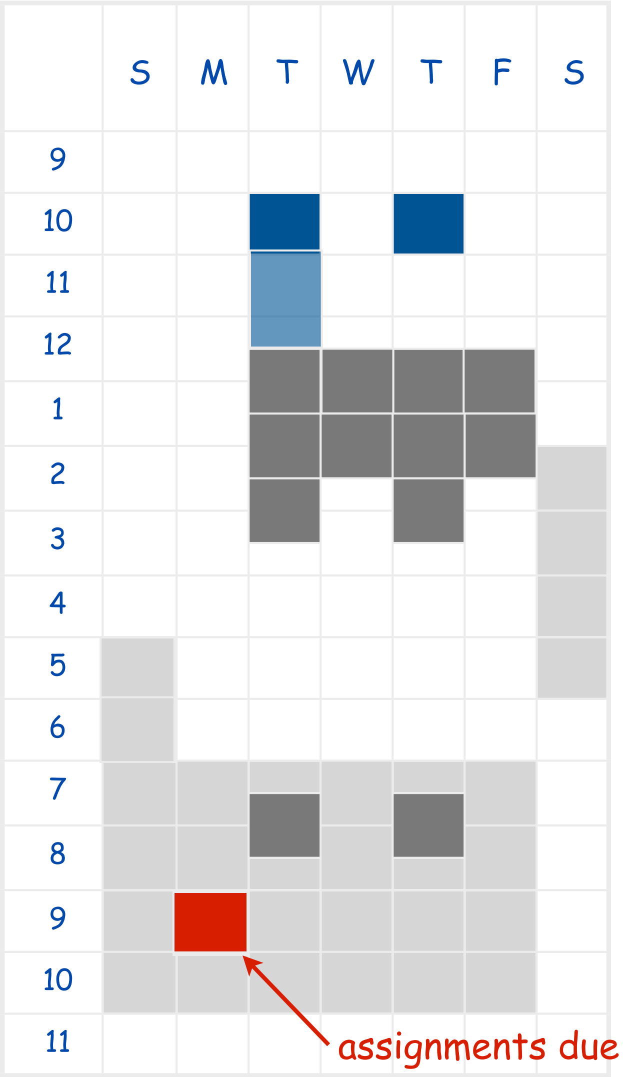
- Tips on assignments / worked examples
- Questions on lecture material.
- Informal and interactive.

⬜ Friend 016/017 lab. [Ugrad assistants]

- Help with systems/debugging.
- No help with course material.

Piazza.

- Best chance of quick response to a question.
- Post to class or private post to staff.



See `www.princeton.edu/~cos126` for full current details and office hours.

Grades

Course grades. No preset curve or quota.

9 programming assignments. 40%.

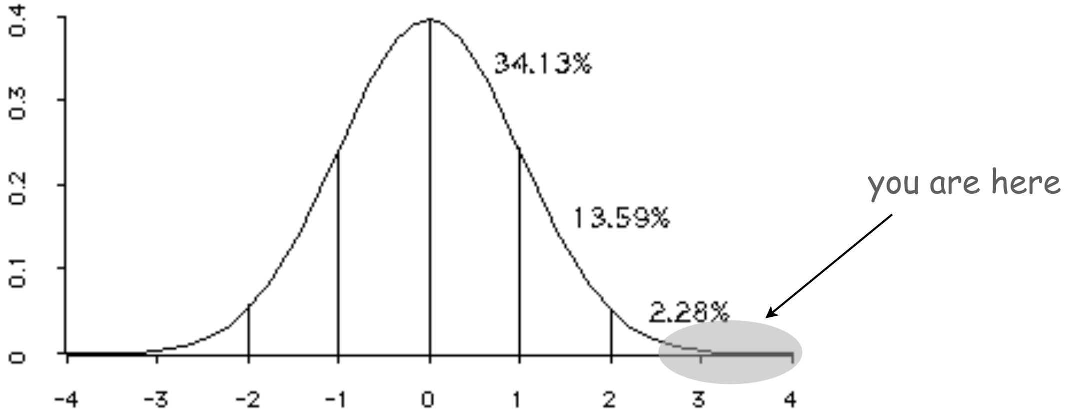
2 written exams (in class, 10/11 and 12/13). 35%.

2 programming exams (evenings, 10/25 and 12/13). 15%.

Final programming project (due Dean's date - 1). 10%.

Extra credit / staff discretion. Adjust borderline cases.

participation helps, frequent absence hurts



Due dates

	Su	Mo	Tu	We	Th	Fr	Sa
SEP					13	14	15
	16	17	18	19	20	21	22
	23	24	25	26	27	28	29
	30						
OCT		1	2	3	4	5	6
	7	8	9	10	11	12	13
	14	15	16	17	18	19	20
	21	22	23	24	25	26	27
	28	29	30	31			
NOV					1	2	3
	4	5	6	7	8	9	10
	11	12	13	14	15	16	17
	18	19	20	21	22	23	24
	25	26	27	28	29	30	
DEC							1
	2	3	4	5	6	7	8
	9	10	11	12	13	14	15
	16	17	18	19	20	21	22
	23	24	25	26	27	28	29
	30	31					
JAN			1	2	3	4	5
	6	7	8	9	10	11	12
	13	14					

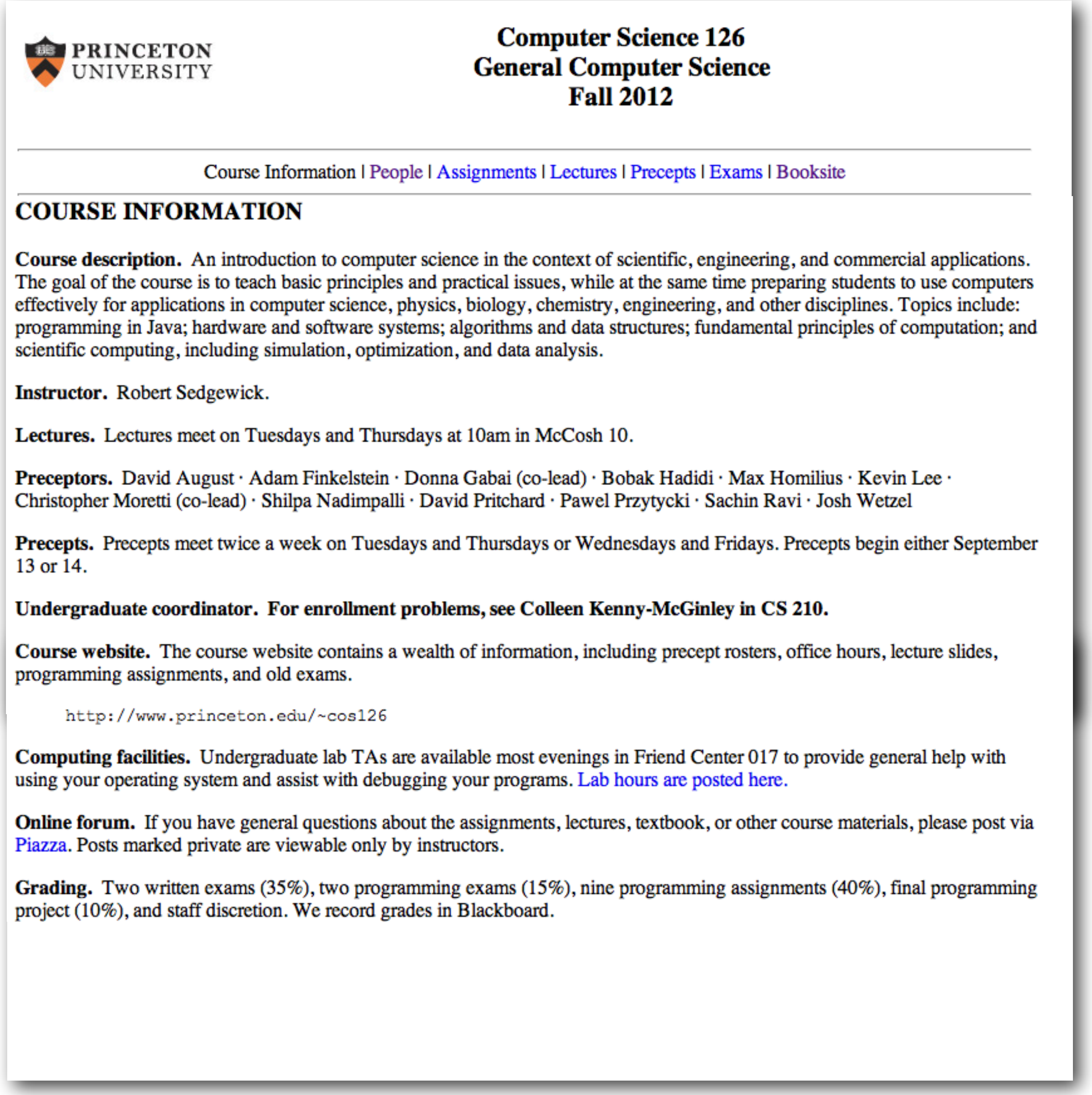
Reading period.

No lectures; precepts T and W.

Course Website

`http://www.princeton.edu/~cos126`

bookmark this!



PRINCETON UNIVERSITY

Computer Science 126
General Computer Science
Fall 2012

Course Information | People | Assignments | Lectures | Precepts | Exams | Booksite

COURSE INFORMATION

Course description. An introduction to computer science in the context of scientific, engineering, and commercial applications. The goal of the course is to teach basic principles and practical issues, while at the same time preparing students to use computers effectively for applications in computer science, physics, biology, chemistry, engineering, and other disciplines. Topics include: programming in Java; hardware and software systems; algorithms and data structures; fundamental principles of computation; and scientific computing, including simulation, optimization, and data analysis.

Instructor. Robert Sedgewick.

Lectures. Lectures meet on Tuesdays and Thursdays at 10am in McCosh 10.

Preceptors. David August · Adam Finkelstein · Donna Gabai (co-lead) · Bobak Hadidi · Max Homilius · Kevin Lee · Christopher Moretti (co-lead) · Shilpa Nadimpalli · David Pritchard · Pawel Przytycki · Sachin Ravi · Josh Wetzel

Precepts. Precepts meet twice a week on Tuesdays and Thursdays or Wednesdays and Fridays. Precepts begin either September 13 or 14.

Undergraduate coordinator. For enrollment problems, see Colleen Kenny-McGinley in CS 210.

Course website. The course website contains a wealth of information, including precept rosters, office hours, lecture slides, programming assignments, and old exams.

`http://www.princeton.edu/~cos126`

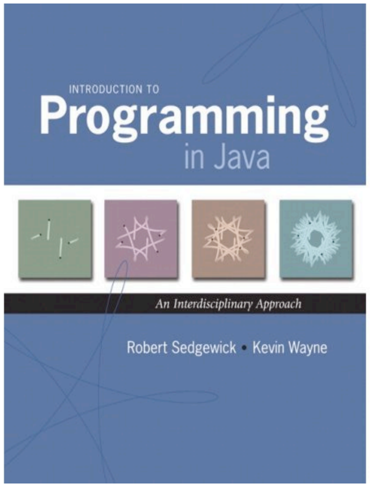
Computing facilities. Undergraduate lab TAs are available most evenings in Friend Center 017 to provide general help with using your operating system and assist with debugging your programs. Lab hours are posted here.

Online forum. If you have general questions about the assignments, lectures, textbook, or other course materials, please post via Piazza. Posts marked private are viewable only by instructors.

Grading. Two written exams (35%), two programming exams (15%), nine programming assignments (40%), final programming project (10%), and staff discretion. We record grades in Blackboard.

Textbook and Booksite

Textbook.

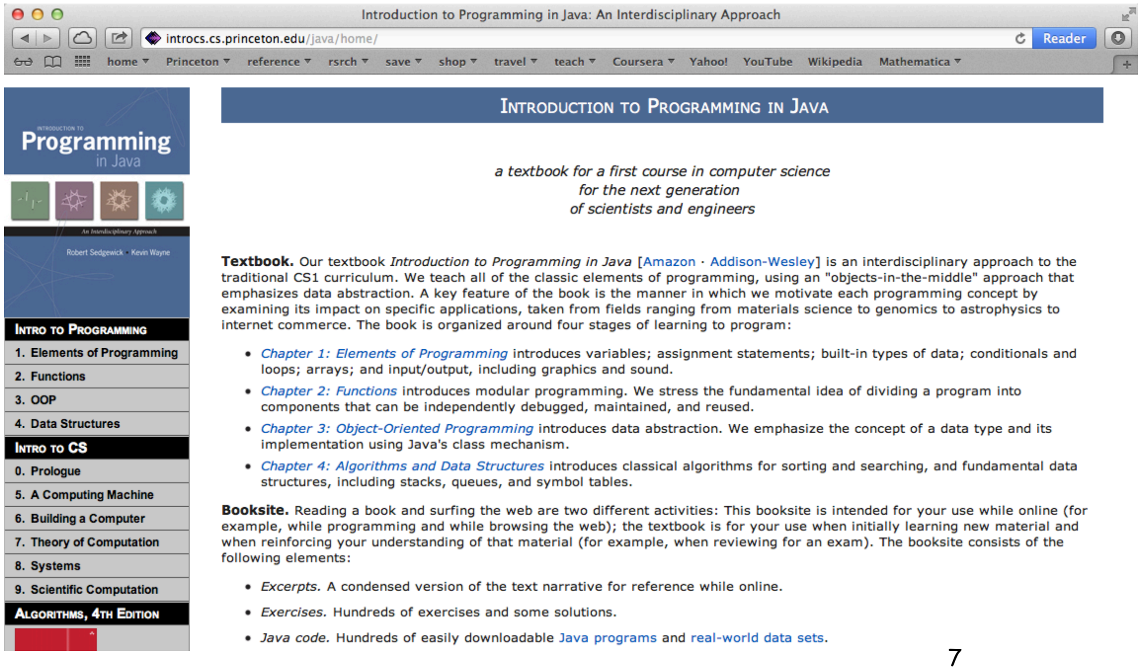


for use while learning and studying

Booksite.

- Summary of content.
- Code, exercises, examples.
- Supplementary material.
- NOT the textbook

for use while online



INTRODUCTION TO PROGRAMMING IN JAVA

a textbook for a first course in computer science
for the next generation
of scientists and engineers

Textbook. Our textbook *Introduction to Programming in Java* [Amazon · Addison-Wesley] is an interdisciplinary approach to the traditional CS1 curriculum. We teach all of the classic elements of programming, using an "objects-in-the-middle" approach that emphasizes data abstraction. A key feature of the book is the manner in which we motivate each programming concept by examining its impact on specific applications, taken from fields ranging from materials science to genomics to astrophysics to internet commerce. The book is organized around four stages of learning to program:

- *Chapter 1: Elements of Programming* introduces variables; assignment statements; built-in types of data; conditionals and loops; arrays; and input/output, including graphics and sound.
- *Chapter 2: Functions* introduces modular programming. We stress the fundamental idea of dividing a program into components that can be independently debugged, maintained, and reused.
- *Chapter 3: Object-Oriented Programming* introduces data abstraction. We emphasize the concept of a data type and its implementation using Java's class mechanism.
- *Chapter 4: Algorithms and Data Structures* introduces classical algorithms for sorting and searching, and fundamental data structures, including stacks, queues, and symbol tables.

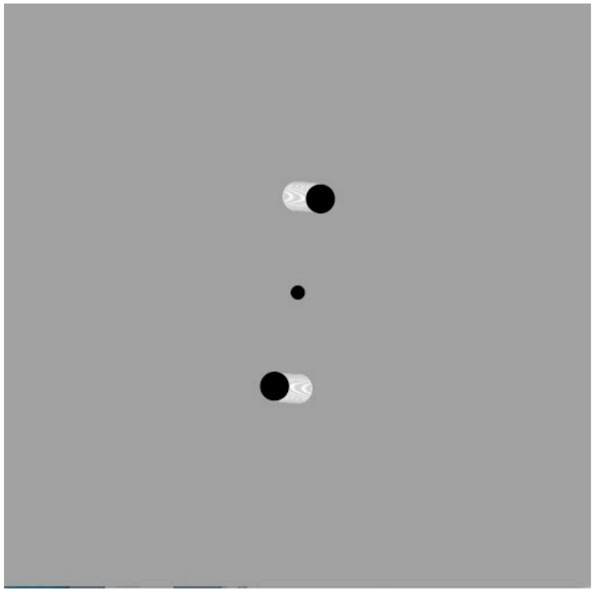
Booksite. Reading a book and surfing the web are two different activities: This booksite is intended for your use while online (for example, while programming and while browsing the web); the textbook is for your use when initially learning new material and when reinforcing your understanding of that material (for example, when reviewing for an exam). The booksite consists of the following elements:

- *Excerpts.* A condensed version of the text narrative for reference while online.
- *Exercises.* Hundreds of exercises and some solutions.
- *Java code.* Hundreds of easily downloadable Java programs and real-world data sets.

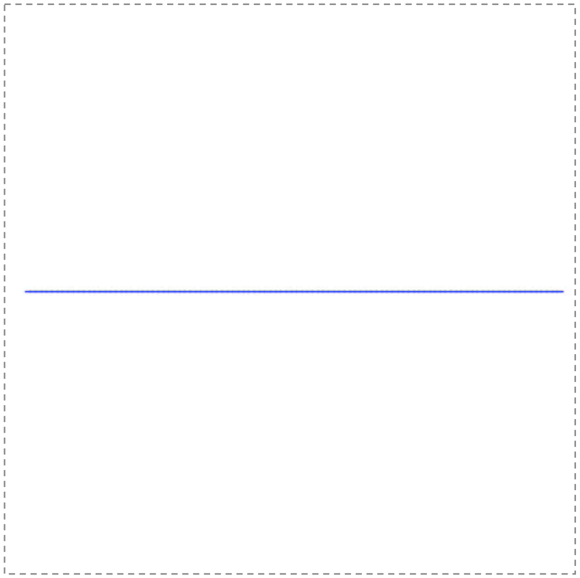
Programming Assignments

Desiderata.

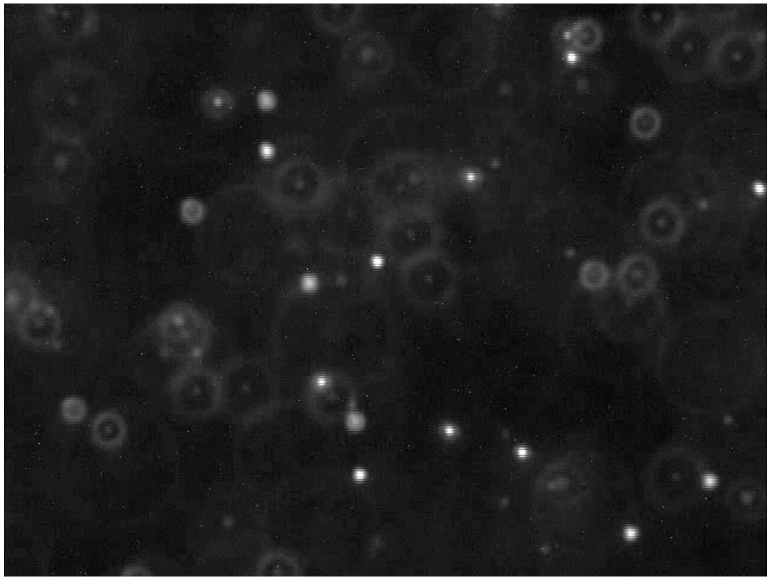
- Address an important scientific or commercial problem.
- Illustrate the importance of a fundamental CS concept.
- You solve problem from scratch!



N-body simulation



pluck a guitar string



estimate Avogadro's number

Programming Assignments

Desiderata.

- Address an important scientific or commercial problem.
- Illustrate the importance of a fundamental CS concept.
- You solve problem from scratch!

Due. Mondays 9pm via Web submission.

Computing equipment.

- Your laptop. [OS X, Windows, Linux, iPhone, …]
- OIT desktop. [Friend 016 and 017 labs]

What's Ahead?

Lecture 2. Intro to Java.

Precept 1. Meets today/tomorrow.

Not registered? Go to any precept now; officially register ASAP.

Change precepts? Use SCORE.

see Colleen Kenny-McGinley in CS 210
if the only precept you can attend is closed

Assignment 0. [www.princeton.edu/~cos126/assignments.php]

- Due Monday 9PM.
- Read Sections 1.1 and 1.2 in textbook.
- Install Java programming environment + a few exercises.
- Lots of help available, don't be bashful.

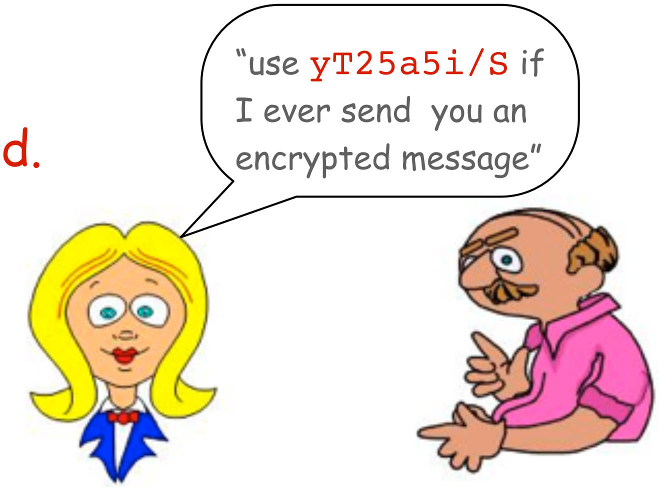
END OF ADMINISTRATIVE STUFF

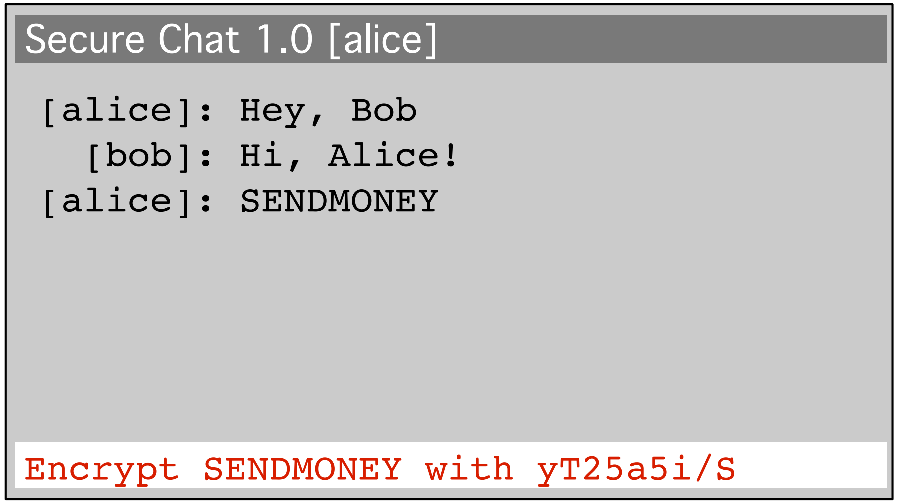
0. Prologue: A Simple Machine

Secure Chat with a One-Time Pad

Alice wants to send a secret message to Bob

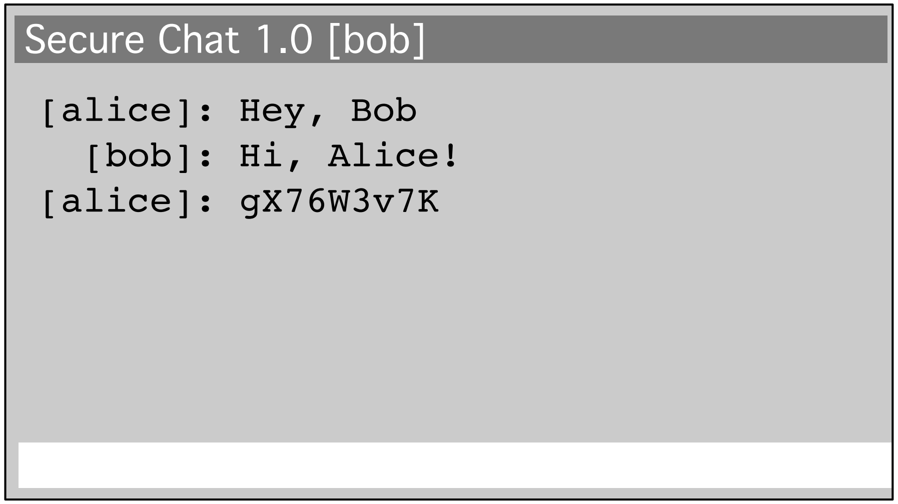
- Sometime in the past, they exchange a one-time pad.
- Alice uses the pad to encrypt the message.




Secure Chat 1.0 [alice]

```
[alice]: Hey, Bob
  [bob]: Hi, Alice!
[alice]: SENDMONEY
```

```
Encrypt SENDMONEY with yT25a5i/S
```

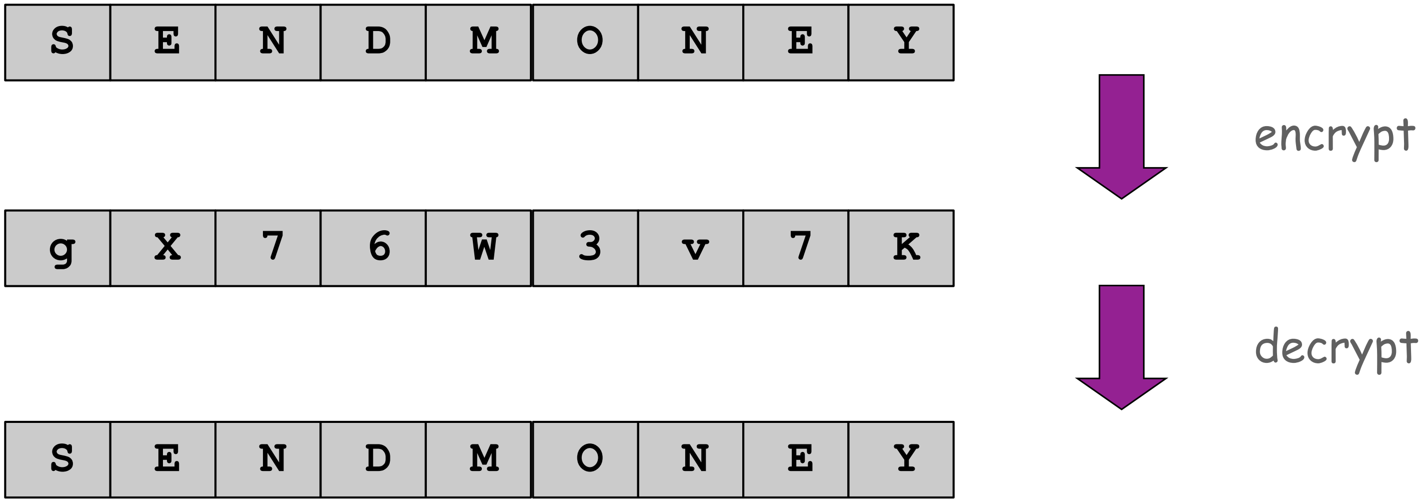

Secure Chat 1.0 [bob]

```
[alice]: Hey, Bob
  [bob]: Hi, Alice!
[alice]: gX76W3v7K
```

Key point: Without the pad, Eve cannot understand the message.

Encryption Machine

Goal. Design a machine to encrypt and decrypt data.



Enigma encryption machine.

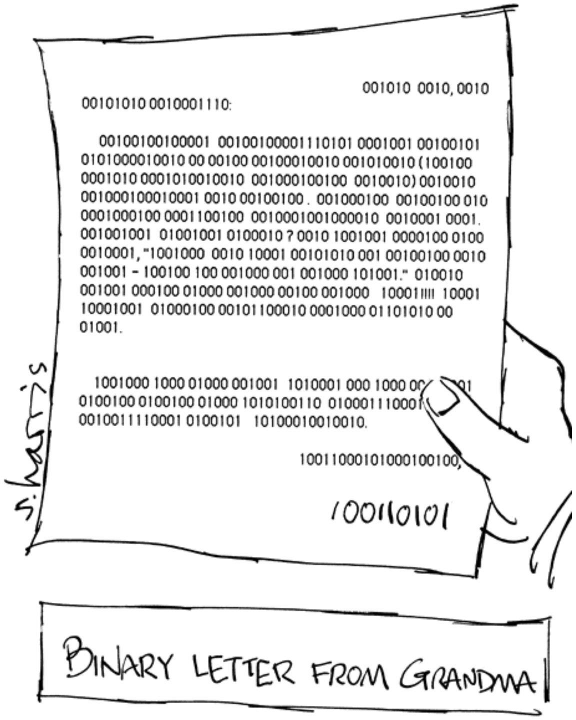
- "Unbreakable" German code during WWII.
- Broken by Turing bombe.
- One of first uses of computers.
- Helped win Battle of Atlantic by locating U-boats.

A Digital World

Data is a sequence of bits. [bit = 0 or 1] ← can use decimal digits, letters, or some other system, but bits are more easily encoded physically ("on-off", "up-down", "hot-cold",...)

- Text.
- Programs, executables.
- Documents, pictures, sounds, movies, …

thousands of bits



Copyright 2004, Sidney Harris
http://www.sciencecartoonsplus.com

billions of bits

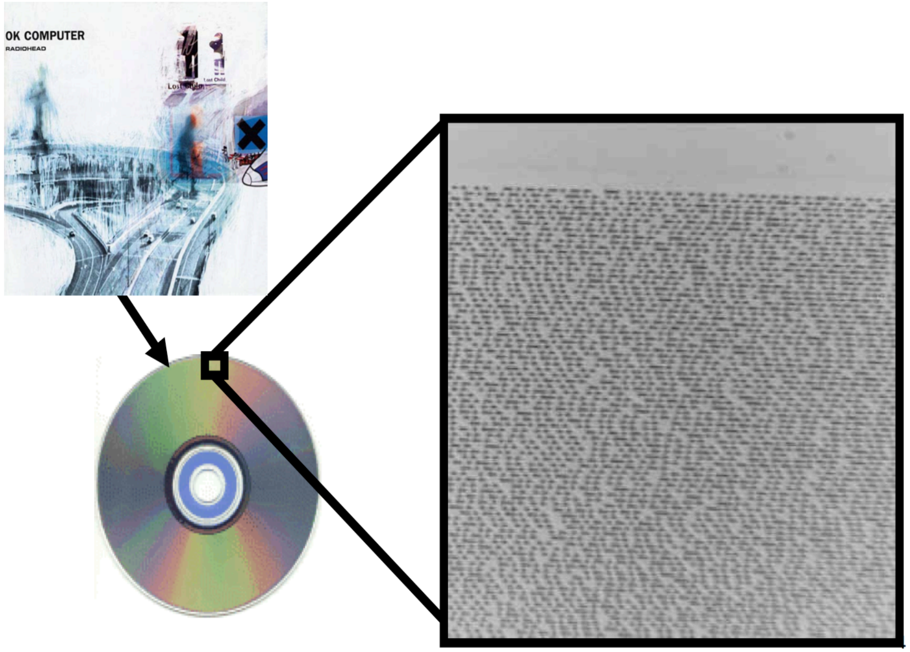


image courtesy of David August

A Digital World

Data is a sequence of bits. [bit = 0 or 1]

- Text.
- Programs, executables.
- Documents, pictures, sounds, movies, …

Ex. Base64 encoding of text.

- Simple method for representing `A-Z`, `a-z`, `0-9`, `+`, `/`
- 6 bits to represent each symbol (64 symbols)

000000 A	001000 I	010000 Q	011000 Y	100000 g	101000 o	110000 w	111000 4
000001 B	001001 J	010001 R	011001 Z	100001 h	101001 p	110001 x	111001 5
000010 C	001010 K	010010 S	011010 a	100010 i	101010 q	110010 y	111010 6
000011 D	001011 L	010011 T	011011 b	100011 j	101011 r	110011 z	111011 7
000100 E	001100 M	010100 U	011100 c	100100 k	101100 s	110100 0	111100 8
000101 F	001101 N	010101 V	011101 d	100101 l	101101 t	110101 1	111101 9
000110 G	001110 O	010110 W	011110 e	100110 m	101110 u	110110 2	111110 +
000111 H	001111 P	010111 X	011111 f	100111 n	101111 v	110111 3	111111 /

Secure Chat with a One-Time Pad

First challenge: Create a one-time pad.

Good choice: A random sequence of bits (stay tuned).

Note: any sequence of bits can be encoded as characters

110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
y	T	2	5	a	5	i	/	S	encoded as characters

One-Time Pad Encryption

Encryption.

- Convert text message to N bits.

Base64 Encoding

char	dec	binary
A	0	000000
B	1	000001
…	…	…
M	12	001100
…	…	…

S	**E**	**N**	**D**	**M**	**O**	**N**	**E**	**Y**	message
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64

One-Time Pad Encryption

Encryption.

- Convert text message to N bits.
- Use N random bits as one-time pad.

S	E	N	D	M	O	N	E	Y	message
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
y	T	2	5	a	5	i	/	S	

One-Time Pad Encryption

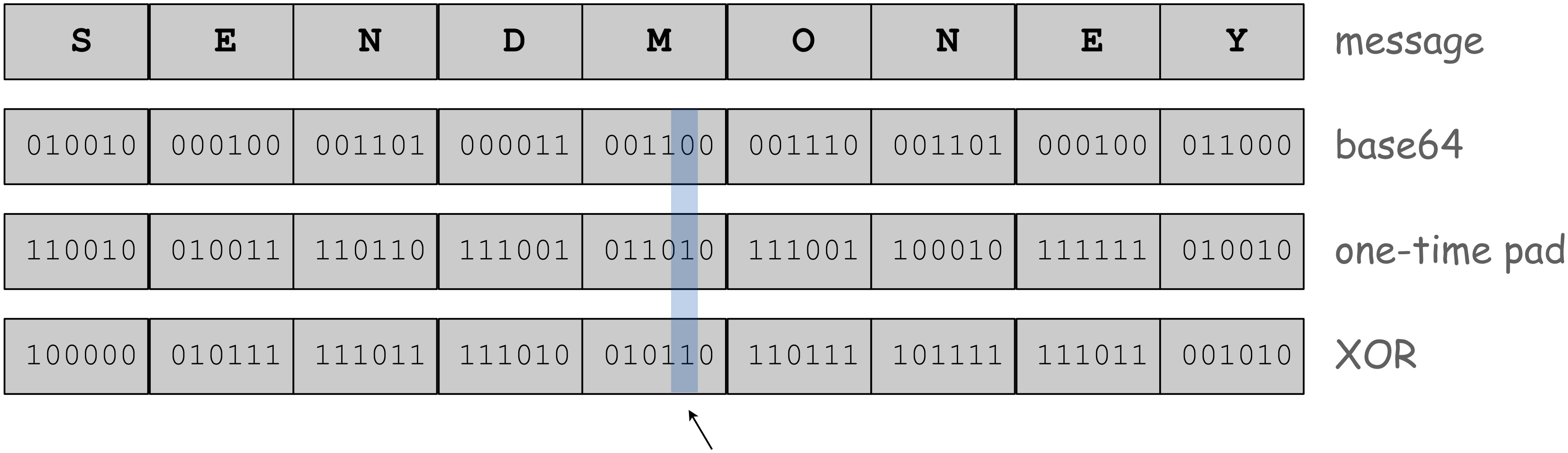
Encryption.

- Convert text message to N bits.
- Use N random bits as one-time pad.
- Take bitwise XOR of two bitstrings.

sum corresponding pair of bits: 1 if sum is odd, 0 if even

XOR Truth Table

x	y	x ^ y
0	0	0
0	1	1
1	0	1
1	1	0



S	**E**	**N**	**D**	**M**	**O**	**N**	**E**	**Y**	message
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
100000	010111	111011	111010	010110	110111	101111	111011	001010	XOR

`0 ^ 1 = 1`

One-Time Pad Encryption

Encryption.

- Convert text message to N bits.
- Use N random bits as one-time pad.
- Take bitwise XOR of two bitstrings.
- Convert binary back into text.

Base64 Encoding

char	dec	binary
A	0	000000
B	1	000001
…	…	…
w	22	010110
…	…	…

S	**E**	**N**	**D**	**M**	**O**	**N**	**E**	**Y**	message
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
100000	010111	111011	111010	010110	110111	101111	111011	001010	XOR
g	**X**	**7**	**6**	**w**	**3**	**v**	**7**	**K**	encrypted

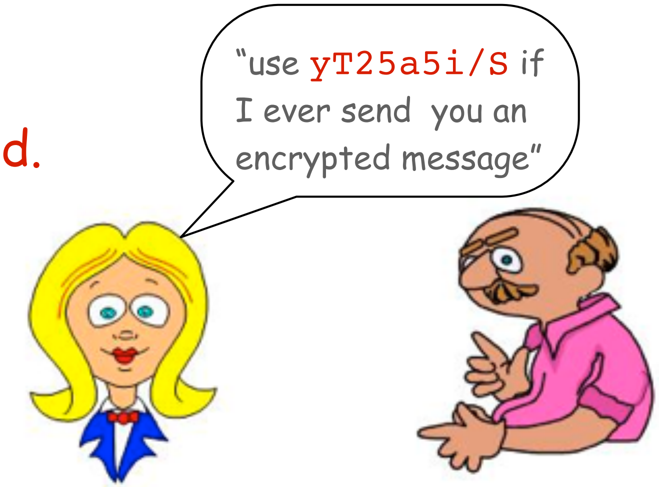
Typical Exam Question (TEQ)

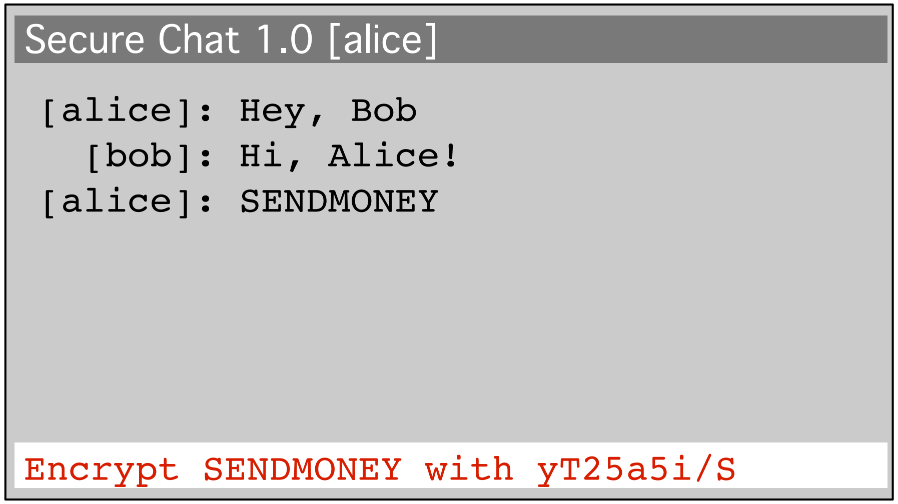
Encrypt the message `E A S Y` with the pad `1 2 3 4`.

Secure Chat with a One-Time Pad

Alice wants to send a secret message to Bob

- Sometime in the past, they exchange a one-time pad.
- Alice uses the pad to encrypt the message.





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Encrypt SENDMONEY with yT25a5i/S
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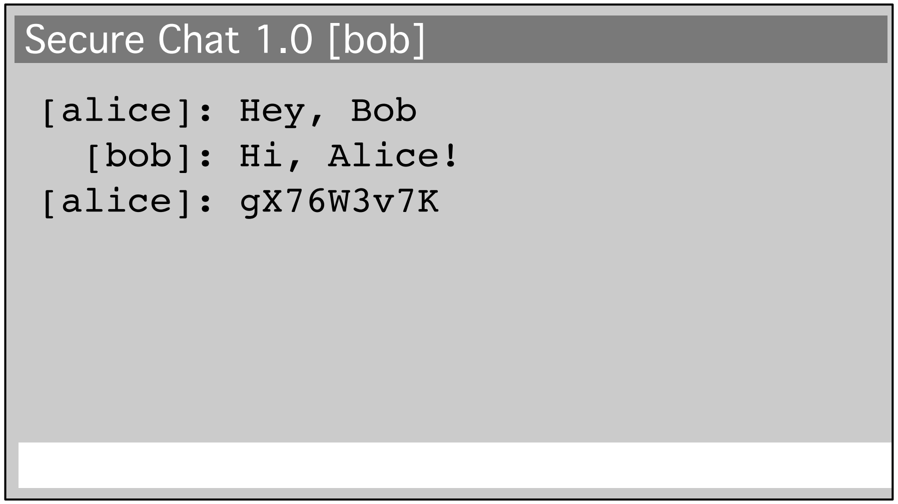


```
[alice]: Hey, Bob
  [bob]: Hi, Alice!
[alice]: gX76W3v7K
```

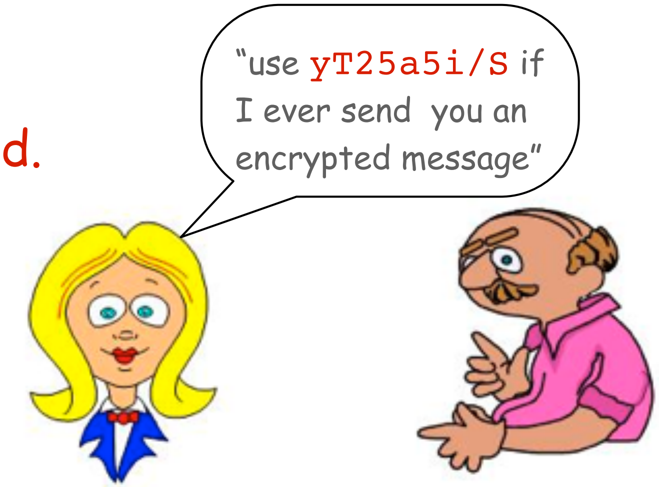
Key point: Without the pad, Eve cannot understand the message.

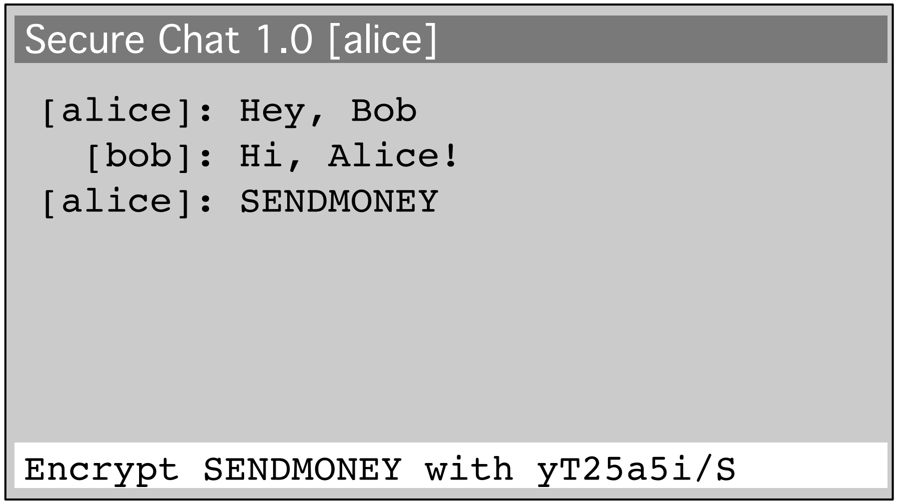
But how can Bob understand the message?

Secure Chat with a One-Time Pad

Alice wants to send a secret message to Bob

- Sometime in the past, they exchange a one-time pad.
- Alice uses the pad to encrypt the message.
- Bob uses the same pad to decrypt the message.





```
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  [bob]: Hi, Alice!
[alice]: SENDMONEY
```

```
Encrypt SENDMONEY with yT25a5i/S
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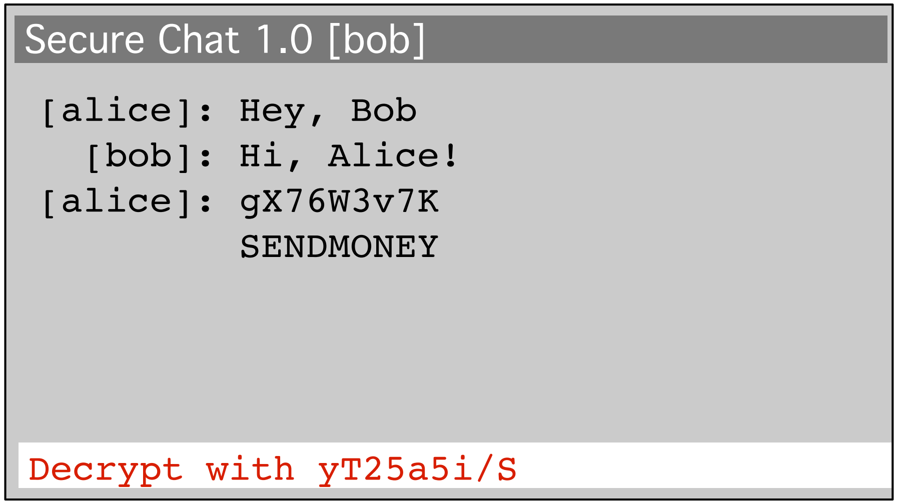


```
[alice]: Hey, Bob
  [bob]: Hi, Alice!
[alice]: gX76W3v7K
         SENDMONEY
```

```
Decrypt with yT25a5i/S
```

Key point: Without the pad, Eve cannot understand the message.

One-Time Pad Decryption

Decryption.

- Convert encrypted message to binary.

`g`	`X`	`7`	`6`	`W`	`3`	`v`	`7`	`K`	encrypted

One-Time Pad Decryption

Decryption.

- Convert encrypted message to binary.

Base64 Encoding

char	dec	binary
A	0	000000
B	1	000001
…	…	…
W	22	010110
…	…	…

g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64

One-Time Pad Decryption

Decryption.

- Convert encrypted message to binary.
- Use same N "random" bits (one-time pad).

g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
y	T	2	5	a	5	i	/	S	

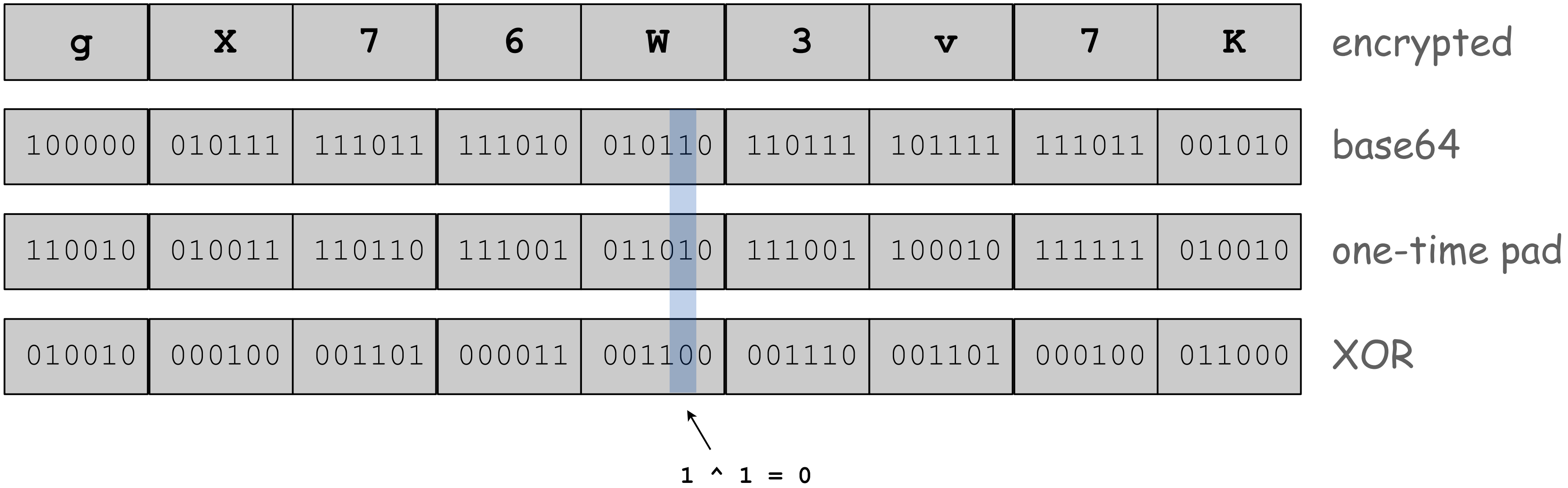
One-Time Pad Decryption

Decryption.

- Convert encrypted message to binary.
- Use same N random bits (one-time pad).
- Take bitwise XOR of two bitstrings.

XOR Truth Table

x	y	x ^ y
0	0	0
0	1	1
1	0	1
1	1	0



g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
010010	000100	001101	000011	001100	001110	001101	000100	011000	XOR

One-Time Pad Decryption

Decryption.

- Convert encrypted message to binary.
- Use same N random bits (one-time pad).
- Take bitwise XOR of two bitstrings.
- Convert back into text.

Base64 Encoding

char	dec	binary
A	0	000000
B	1	000001
…	…	…
M	12	001100
…	…	…

g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
010010	000100	001101	000011	001100	001110	001101	000100	011000	XOR
S	E	N	D	M	O	N	E	Y	message

magic?

Why Does It Work?

Crucial property. Decrypted message = original message.

Notation	Meaning
a	original message bit
b	one-time pad bit
^	XOR operator
a ^ b	encrypted message bit
(a ^ b) ^ b	decrypted message bit

Why is crucial property true?

- Use properties of XOR.
- (a ^ b) ^ b = a ^ (b ^ b) = a ^ 0 = a

associativity of ^

always 0

identity

XOR Truth Table

x	y	x ^ y
0	0	0
0	1	1
1	0	1
1	1	0

One-Time Pad Decryption (with the wrong pad)

Decryption.

- Convert encrypted message to binary.

`g`	`X`	`7`	`6`	`W`	`3`	`v`	`7`	`K`	encrypted

One-Time Pad Decryption (with the wrong pad)

Decryption.

- Convert encrypted message to binary.

`g`	`X`	`7`	`6`	`W`	`3`	`v`	`7`	`K`	encrypted
`100000`	`010111`	`111011`	`111010`	`010110`	`110111`	`101111`	`111011`	`001010`	base64

One-Time Pad Decryption (with the wrong pad)

Decryption.

- Convert encrypted message to binary.
- Use wrong N bits (bogus one-time pad).

g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
101000	011100	110101	101111	010010	111001	100101	101010	001010	wrong bits

One-Time Pad Decryption (with the wrong pad)

Decryption.

- Convert encrypted message to binary.
- Use wrong N bits (bogus one-time pad).
- Take bitwise XOR of two bitstrings.

g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
101000	011100	110101	101111	010010	111001	100101	101010	001010	wrong bits
001000	001011	001110	010101	000100	001110	001010	010001	000000	XOR

One-Time Pad Decryption (with the wrong pad)

Decryption.

- Convert encrypted message to binary.
- Use wrong N bits (bogus one-time pad).
- Take bitwise XOR of two bitstrings.
- Convert back into text: Oops.

g	X	7	6	W	3	v	7	K	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
101010	110000	000011	100000	011011	000011	101110	011010	101111	wrong bits
001010	100111	111000	011010	001101	110100	000001	100001	100101	XOR
K	n	4	a	N	0	B	h	l	wrong message [usually gibberish]

Eve's Problem (one-time pads)

Key point: Without the pad, Eve cannot understand the message.

But Eve has a computer. Why not try all possible pads?

One problem: it might take a long time [stay tuned].

Worse problem: she would see all possible messages!

- 54 bits
- 2^{54} possible messages, all different.
- 2^{54} possible encoded messages, all different.
- No way for Eve to distinguish real message from any other message.

One-time pad is "provably secure".

AAAAAAAAA	gX76W3v7K
AAAAAAAAB	gX76W3v7L
AAAAAAAAC	gX76W3v7I
...	
qwDgbDuav	Kn4aN0Bhl
...	
tTtpWk+1E	NEWTATTOO
...	
yT25a5i/S	SENDMONEY
...	
////////+	fo7FpIQE0
/////////	fo7FpIQE1

Goods and Bads of One-Time Pads

Good.

- Easily computed by hand.
- Very simple encryption/decryption processes.
- Provably unbreakable if bits are truly random. [Shannon, 1940s]

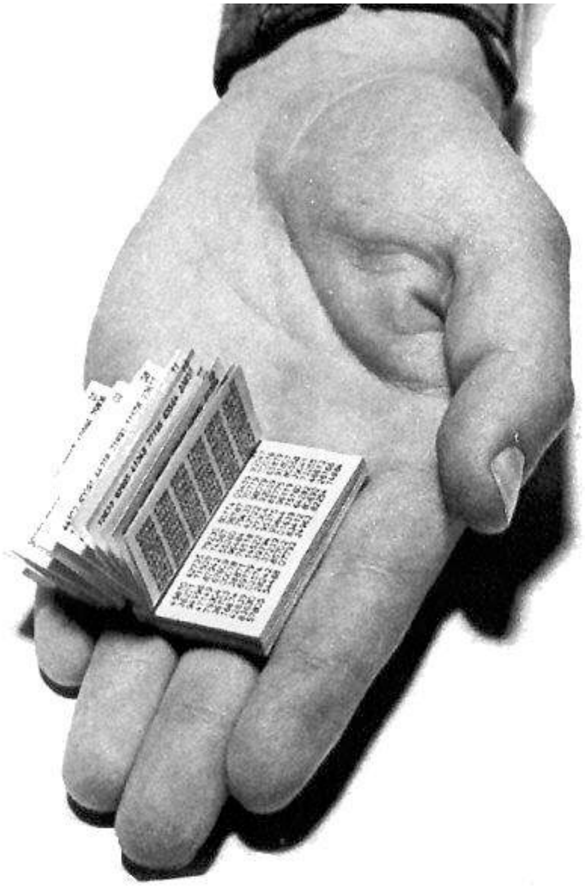
eavesdropper Eve sees only random bits

"one time" means one time only

Bad.

- Easily breakable if pad is re-used.
- Pad must be as long as the message.
- Truly random bits are very hard to come by.
- Pad must be distributed securely.

impractical for Web commerce



a Russian one-time pad

Pseudo-Random Bit Generator

Practical middle-ground.

- Make a "random" bit generator gadget.
- Alice and Bob each get identical small gadgets
  [same gadget works for both]
- Alice and Bob also each get identical books of small seeds.

instead of identical
large one-time pads

Goal. Small gadget that produces a long sequence of bits.

Pseudo-Random Bit Generator

Small deterministic gadgets that produce long sequences of pseudo-random bits:

- Enigma
- Linear feedback shift register.
- Linear congruential generator.
- Blum-Blum-Shub generator.
- [many others have been invented]

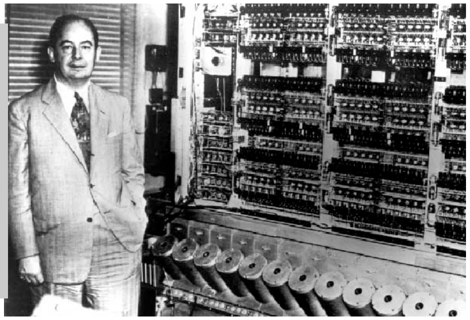
Pseudo-random? Bits are not really random:

- Bob's and Alice's gadgets must produce the same bits from the same seed.
- Bits must have as many properties of random bits as possible (to foil Eve).

↑

Ex 1. approx 1/2 0s and 1/2 1s
Ex 2. approx 1/4 each of 00, 01, 10 11

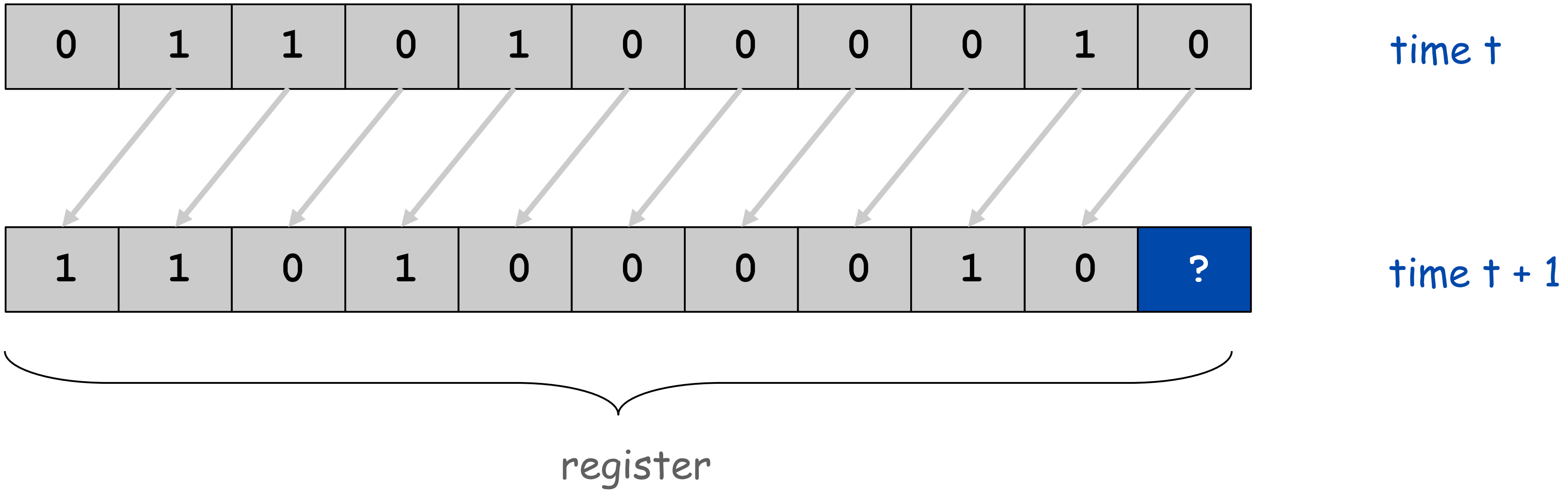
> *" Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin. "*
>
> *– John von Neumann (left)*
>
> *– ENIAC (right)*



Shift Register

Shift register terminology.

- Bit: 0 or 1.
- Cell: storage element that holds one bit.
- Register: sequence of cells.
- Seed: initial sequence of bits.
- Shift register: when clock ticks, bits propagate one position to left.

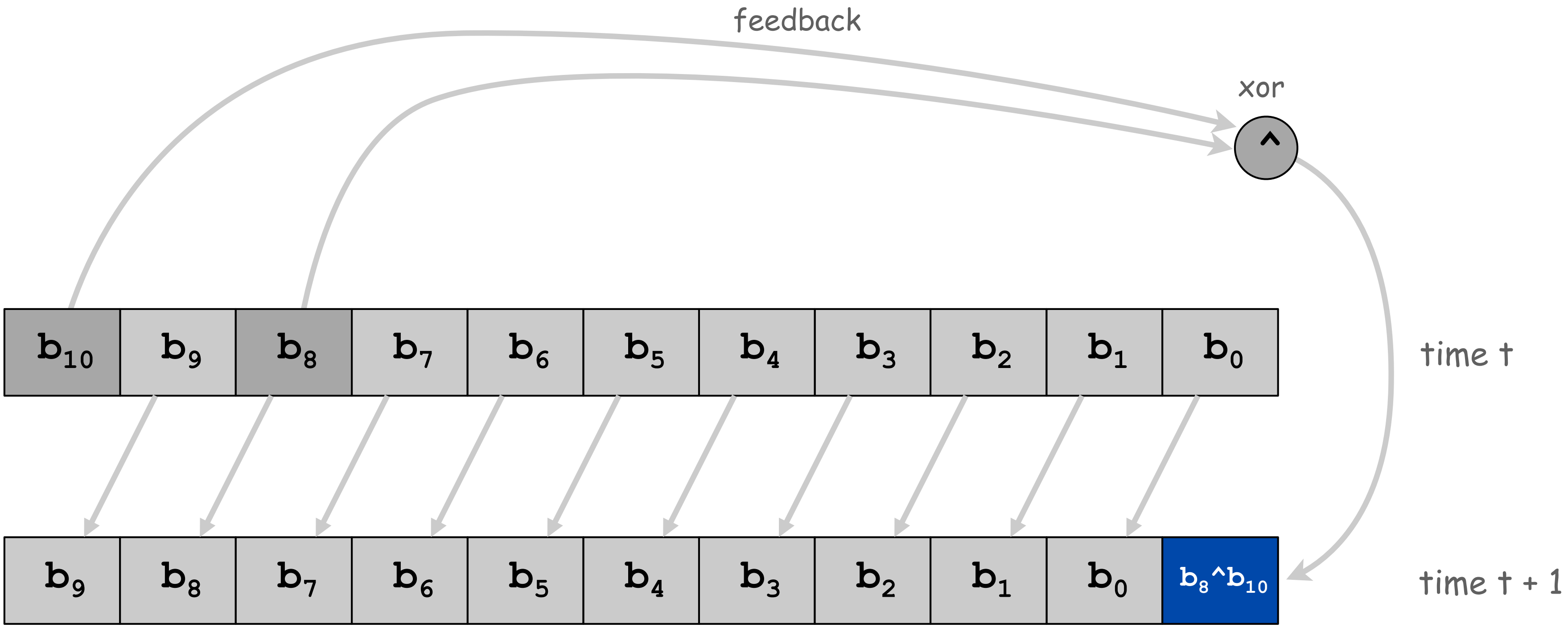


0	1	1	0	1	0	0	0	0	1	0	time t
1	1	0	1	0	0	0	0	1	0	?	time t + 1

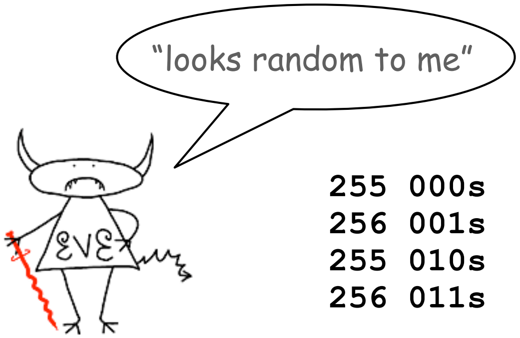
Linear Feedback Shift Register (LFSR)

{8, 10} linear feedback shift register.

- Shift register with 11 cells.
- Bit b_0 is XOR of previous bits b_8 and b_{10}.
- Pseudo-random bit = b_0.



Random Numbers



```
255 000s
256 001s
255 010s
256 011s
...
```

Q. Are these 2000 numbers random?

If not, what is the pattern?

```
1100100100111101101110010110101110011000101111110100100001001101001011110011001001111111011100
0001010110001000011101010011010000111100100110011101111111010100000100001000101001010100011000
0010111100010010011010110111100011010011011100111101011110010001001110101011101000001010010001
0001101010101110000000101100000100111000101110110100101011001100001111111001100000111111000110
0001101111001110100111101001110010011101110111010101010100000000001000000001010000001000100001
0101010010000000110100000111001000110111010111010100010100001010001001000101011010100001100001
0011110010111001110010111101110010010101110110000101011100100001011101001001010011011000111101
1101100101010111100000010011000010111110010010001110110101101011000110001110111101101010010110
0001100111001111110111100001010011001000111111010110000100011100101011011100001101011001110001
1111011011000101101110100110101001111000011100110011011111111101000000010010000010110100010011
0010101111110000100001100101001111100011100011011011011101101101010110110000011011100011101011
0110100011011001011101111001010100111000001110110001101011101110001010101101000000110010000111
1101001100010011111010111000100010110101010011000000111110000110001100111101111110010100001110
0010011011010111101100010010111010110010100011110001011001101001111110011100001111011001100101
1111111001000000111010000110100100111001101110111110101010001000000101010000100000100101000101
1000101001110100011101001011010011001100111111111110000000001100000001111000001100110001111111
1011000000101110000100101100101100111100111110011110001111001101100111110111110001010001101000
1011100101001011100011001011011111001101000111110010110001110011101101111010110100100011001101
0111111100010000011010100011100001011011001001101111011110100101001001100011011111011101000101
0100101000001100010001111010101100100000111101000110010010111110110010001011110101001001000011
0110100111011001110101111101000100010010101010110000000111000000110110000111011100110101011111
10000010001100010101111010
```

A. No. This is output of {8, 10} LFSR with seed 01101000010!

LFSR Encryption

Encryption.

- Convert text message to N bits.
- Initialize LFSR with given seed
- Generate N bits with LFSR.
- Take bitwise XOR of two bitstrings.
- Convert binary back into text.

Base64 Encoding

char	dec	binary
A	0	000000
B	1	000001
…	…	…
W	22	010110
…	…	…

S	**E**	**N**	**D**	**M**	**O**	**N**	**E**	**Y**	message
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	LFSR bits
100000	010111	111011	111010	010110	110111	101111	111011	001010	XOR
g	**X**	**7**	**6**	**W**	**3**	**v**	**7**	**K**	encrypted

LFSR Decryption

Decryption.

- Convert encrypted message to binary.
- Initialize identical LFSR with same seed
- Generate N bits with LFSR.
- Take bitwise XOR of two bitstrings.
- Convert back into text.

Base64 Encoding

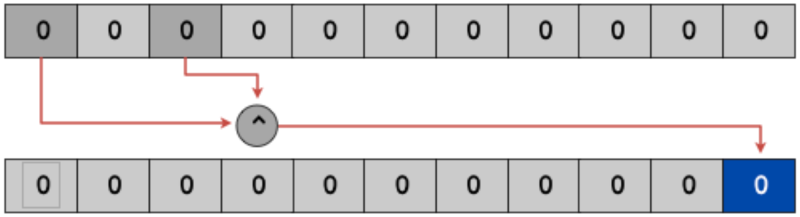
char	dec	binary
A	0	000000
B	1	000001
…	…	…
M	12	001100
…	…	…

g	**X**	**7**	**6**	**W**	**3**	**v**	**7**	**K**	encrypted
100000	010111	111011	111010	010110	110111	101111	111011	001010	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	LFSR bits
010010	000100	001101	000011	001100	001110	001101	000100	011000	XOR
S	**E**	**N**	**D**	**M**	**O**	**N**	**E**	**Y**	message

Key properties of LFSRs

Property 1: A zero fill (all 0s) produces all 0s.

- Don't use all 0s as a seed!
- Fill of all 0s will not otherwise occur.



Property 2: Bitstream must eventually cycle.

- 2^N-1 nonzero fills in an N-bit register.
- Future output completely determined by current fill.

Ex: (1, 2) LFSR

001
010
101
011
111
110
100
001 $2^3-1 = 7$

Property 3: Cycle length in an N-bit register is at most 2^N-1.

- Could be smaller; cycle length depends on tap positions.
- Need higher math (theory of finite groups) to know tap positions for given N.

Bottom line: 11-bit register generates at most 2047 bits before cycling, so use a longer register (say, N = 61).

↖ challenge for the bored: what tap positions?

Eve's Problem (LFSR encryption/decryption)

Key point: Without the (short) seed
Eve cannot understand the (long) message.

But Eve has a computer. Why not try all possible seeds?

assume Eve has a machine (knows LFSR length and taps)

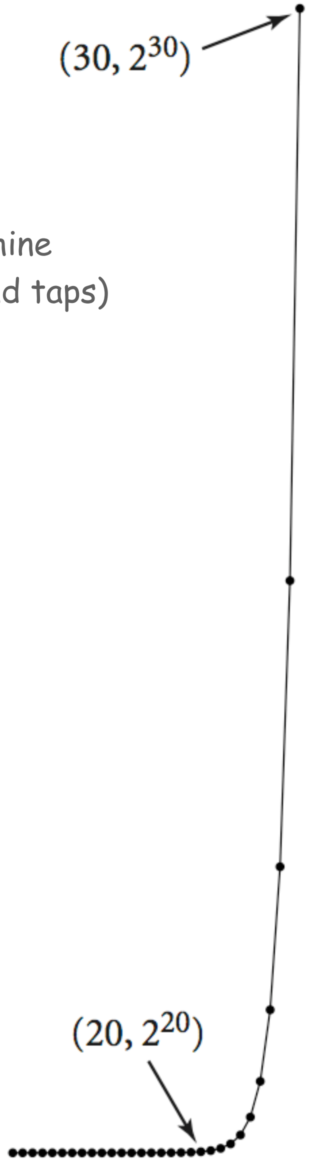
- Seeds are short, messages are long.
- All seeds give a tiny fraction of all messages.
- Extremely likely that all but real seed will produce gibberish.

Bad news (for Eve): There are still too many possibilities!

- Ex: 61-bit register implies 2^{61} possibilities.
- If Eve could check 1 million seeds per second, it would take her 730 centuries to try them all!

Exponential growth dwarfs technological improvements [stay tuned].

- 1000 bits: 2^{1000} possibilities.
- Age of the universe in microseconds: 2^{70}



Goods and Bads of LFSRs

Good.

- Easily computed with simple machine.
- Very simple encryption/decryption processes.
- Bits have many of the same properties as random bits.
- Scalable: 20 cells for 1 million bits; 30 cells for 1 billion bits.

  [but need theory of finite groups to know where to put taps]

a commercially available LFSR

Bad.

- Still need secure, independent way to distribute LFSR seed.
- The bits are not truly random.

  [bits in our 11-bit LFSR cycle after $2^{11} - 1 = 2047$ steps]
- Experts have cracked LFSR encryption.

  [need more complicated machines]

Other LFSR Applications

What else can we do with a LFSR?

- DVD encryption with CSS.
- DVD decryption with DeCSS!
- Subroutine in military cryptosystems.

```
/*     efdtt.c     Author:  Charles M. Hannum <root@ihack.net>             */
/*     Usage is:  cat title-key scrambled.vob | efdtt >clear.vob            */

#define m(i)(x[i]^s[i+84])<<

                   unsigned char x[5]      ,y,s[2048];main(
                   n){for( read(0,x,5     );read(0,s ,n=2048
                            ); write(1   ,s,n)         )if(s
                  [y=s      [13]%8+20]  /16%4  ==1      ){int
                  i=m(      1)17  ^256 +m(0)   8,k      =m(2)
                  0,j=      m(4)   17^ m(3)   9^k*     2-k%8
                  ^8,a     =0,c    =26;for   (s[y]    -=16;
                 --c;j  *=2)a=     a*2^i&    1,i=i /2^j&1
                 <<24;for(j=        127;     ++j<n;c=c>
                                    y)
                                    c

                           +=y=i^i/8^i>>4^i>>12,
                  i=i>>8^y<<17,a^=a>>14,y=a^a*8^a<<6,a=a
                >>8^y<<9,k=s[j],k         ="7Wo~'G_\216"[k
                 &7]+2^"cr3sfw6v;*k+>/n."[k>>4]*2^k*257/
                       8,s[j]=k^(k&k*2&34)*6^c+~y
                                  ;}}
```

http://www.cs.cmu.edu/~dst/DeCSS/Gallery

Typical Exam Question (TEQ) on LFSRs 1

Give first 10 steps of {3, 4} LFSR with initial fill `00001`.

TEQ on LFSRs 2

Goal. Decrypt/encrypt 300 characters (1800 bits).

Challenge. Is it a good idea to use an 11-bit LFSR?

A. Yes, no problem.

B. No, the bits it produces are not truly random.

C. No, need a longer LFSR.

D. No, experts have cracked LFSRs

LFSR and "General Purpose Computer"

Important properties.

- Built from simple components.
- Scales to handle huge problems.
- Requires a deep understanding to use effectively.

Basic Component	LFSR	Computer
control	start, stop, load	same
clock	regular pulse	2.8 GHz pulse
memory	11 bits	1 GB
input	seed	sequence of bits
computation	shift, XOR	logic, arithmetic, …
output	pseudo-random bits	Sequence of bits

Critical difference. General purpose machine can be programmed to simulate ANY abstract machine.

A Profound Idea

Programming. Can write a Java program to simulate the operations of any abstract machine.

- Basis for theoretical understanding of computation. [stay tuned]
- Basis for bootstrapping real machines into existence. [stay tuned]

Stay tuned. See Assignment 5.

```
public class LFSR
{
    private int[] seed;
    private int tap;
    private int N;

    public LFSR(String seed, int tap) { … }

    public int step() { … }

    public static void main(String[] args)
    {
       LFSR lfsr = new LFSR("01101000010", 8);
       for (int i = 0; i < 2000; i++)
          StdOut.println(lfsr.step());
   }
}
```

```
% java LFSR
1100100100111101101110010110101
1100110001011111101001000010011
0100101111001100100111...
```

A Profound Question

Q. What is a random number?

LFSR does not produce random numbers.

- It is a very simple deterministic machine.
- Not obvious how to distinguish the bits it produces from random.
- Experts have figured out how to do so.

Q. Are random processes found in nature?

- Motion of cosmic rays or subatomic particles?
- Mutations in DNA?

Q. Is the natural world a (not-so-simple) deterministic machine?

> *" God does not play dice. "*
>
> *– Albert Einstein*