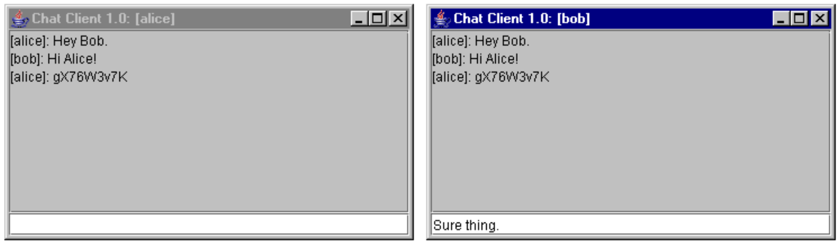
General Computer Science
Princeton University
Spring 2014

Douglas Clark

0. Prologue: A Simple Machine

Secure Chat

Alice wants to send a secret message to Bob
- Can you read the secret message gX76W3v7K ?
- But Bob can. How?



Encryption Machine

Goal. Design a machine to encrypt and decrypt data.

S	E	N	D	M	O	N	E	Y

encrypt

g	X	7	6	W	3	v	7	K

decrypt

S	E	N	D	M	O	N	E	Y

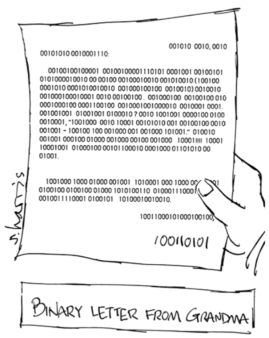
Enigma encryption machine.
- "Unbreakable" German code during WWII.
- Broken by Turing bombe.
- One of first uses of computers.
- Helped win Battle of Atlantic by locating U-boats.

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



billions of bits

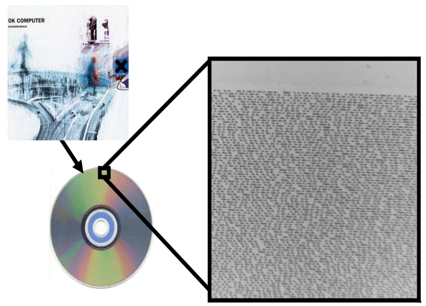


image courtesy of David August

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 /

One-Time Pad Encryption

Encryption.

- Convert text message to N bits. [0 or 1]

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.
- Generate N random bits (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	random bits

One-Time Pad Encryption

XOR Truth Table

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

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
alternatively: 1 if bits are different, 0 if the same

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

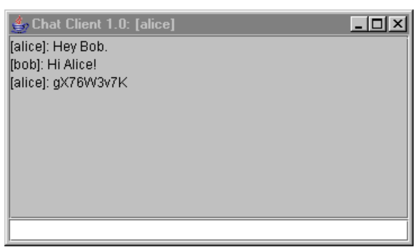
char	dec	binary
A	0	000000
B	1	000001
…	…	…
W	22	010110
…	…	…

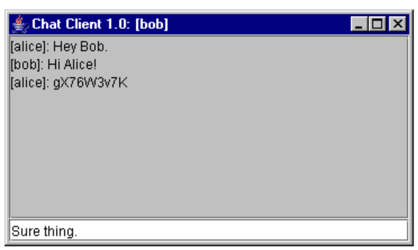
S	E	N	D	M	O	N	E	Y	message
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
100000	010111	111011	111010	010110	110111	101111	111011	001010	XOR
g	X	7	6	W	3	v	7	K	encrypted

Secure Chat

Alice wants to send a secret message to Bob

- Can you read the secret message gX76W3v7K ?
- But Bob can. How?





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
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…	…	…
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).
  - Key point: Bob and Alice agreed on the one-time pad beforehand

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	random bits

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
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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

1 ^ 1 = 0

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
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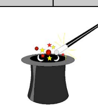
110010	010011	110110	111001	011010	111001	100010	111111	010010	one-time pad
010010	000100	001101	000011	001100	001110	001101	000100	011000	XOR
S	E	N	D	M	O	N	E	Y	message



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

XOR Truth Table

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

Why is crucial property true?

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

associativity of ^   always 0   identity

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
101000	011100	110101	101111	010010	111001	100101	101010	001010	wrong bits
001000	001011	001110	010101	000100	001110	001010	010001	000000	XOR
I	L	O	V	E	O	K	R	A	wrong message

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".

→ IF pad is random and used only once

AAAAAAAAA	gX76W3v7K
AAAAAAAAB	gX76W3v7L
AAAAAAAAC	gX76W3v7I
...	
oc1tS5lqK	ILOVEOKRA
...	
qwDgbDuav	Kn4aN0Bhl
...	
tTtpWk+1E	NEWTATTOO
...	
yT25a5i/S	SENDMONEY
...	
////////+	fo7FpIQE0
/////////	fo7FpIQE1

Goods and Bads of One-Time Pads

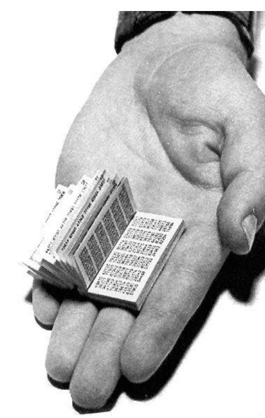
Good.

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

eavesdropper Eve sees only random bits

Bad.

- (After a short break . . .)



a Russian one-time pad

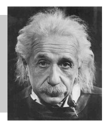
COS 126 Overview

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*



The Basics

Lectures. [Clark]

Precepts. [Pritchard · Ararat · Boyko · Chen · Fan · Gabai · Ghasemi · Ginsburg · Hristov · Israel · Kang · Lee · Shi · Song · Vithanage · Wang · Yang · Zhao]
- Tips on assignments, worked examples, clarify lecture material.
- Informal and interactive.

Friend 016/017 lab.
- Undergraduate lab assistants.
- Help with systems and debugging.

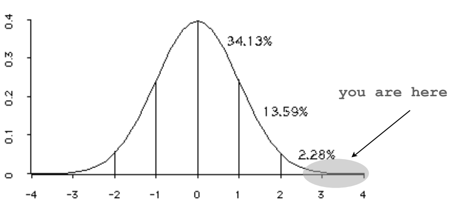
Piazza. [online discussion]
- Best chance for quick response to a question.
- Post to class or via private post to staff.

Website knows all: www.princeton.edu/~cos126

Grades

Course grades. No preset "curve" or quota.

9 programming assignments. 40%.
2 written exams (in lecture, midterm week & last week). 35%.
2 programming exams (evenings, same weeks). 15%.
Final programming project (due Dean's date - 1). 10%.

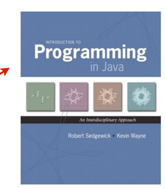


Course Materials

Course website. [www.princeton.edu/~cos126]
- Submit assignments.
- Programming assignments.
- Lecture slides ← (print before lecture) annotate during lecture
- "Booksite".
  - Summary of course content.
  - Code, exercises, examples.
  - Supplementary material.
  - NOT the same as Text
  - for use while online

Course text. [Sedgewick and Wayne]
- Full introduction to course material
- Developed for this course
- For use while learning and studying

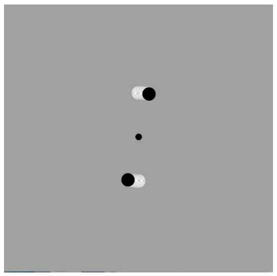
skin before lecture; read thoroughly afterwards

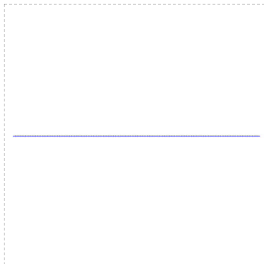


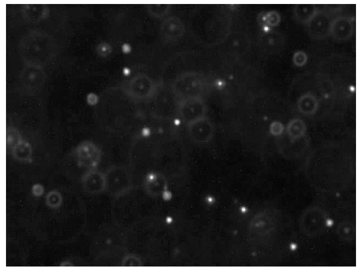
Recommended reading (lectures 19-20). [Harel]

Programming Assignments

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


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 on your own computer!

Due. Mondays midnight via Web submission.

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

Advice.
- Start early; plan multiple sessions.
- Seek help when needed. (Our job is to help you!)
- Use the Piazza online forum for Q&A about assignments, course material.

What's Ahead?

Lecture 2. Intro to Java.

Precept 1. Meets today/tomorrow.

Not registered? Go to any precept now; officially register ASAP.
Need to Change precepts? Use SCORE.

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

Assignment 0.
- Due Monday midnight.
- Read Sections 1.1 and 1.2 in textbook.
- Install Java programming environment (find directions in Assignment 0)
- Lots of help available, don't be bashful.

END OF ADMINISTRATIVE STUFF

Goods and Bads of One-Time Pads

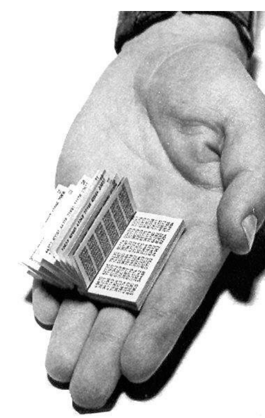
Good.
- Easily computed by hand.
- Very simple encryption/decryption processes.
- Provably unbreakable if bits are truly random. [Shannon, 1940s]

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. ← instead of identical large one-time pads
- also, matching initial values, or "seeds," for their gadgets

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:

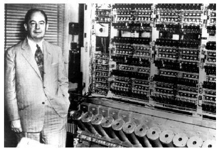
- Enigma
- Linear feedback shift register.
- Linear congruential generator.
- Blum-Blum-Shub generator.
- [many others have been invented]

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

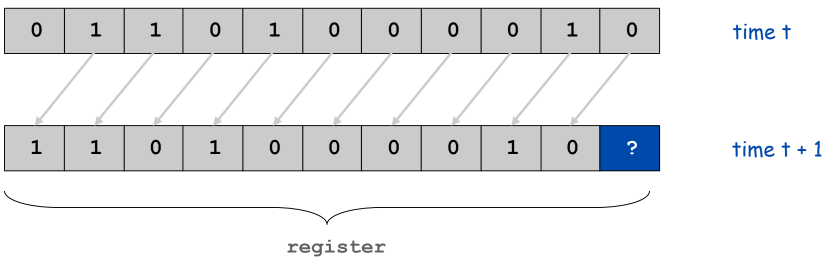
> *" Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin. "*
> *– John von Neumann (left)*
> *– ENIAC (right)*



Shift Register

Shift register terminology.

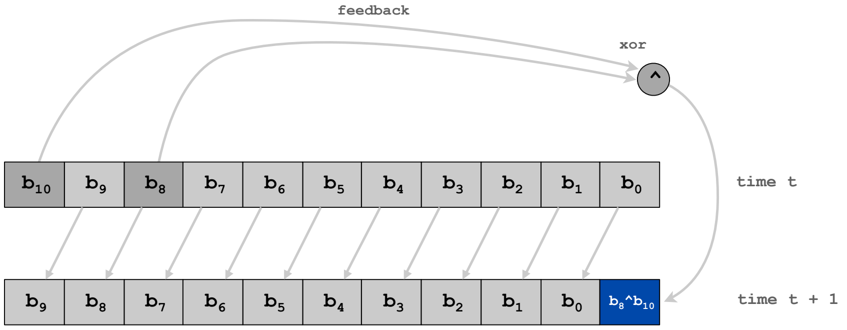
- Bit: 0 or 1.
- Cell: storage element that holds one bit.
- Register: sequence of cells.
- Seed: initial sequence of bits.
- Shift register: when clock ticks, bits propagate one position to left.



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 = (new) b_0.

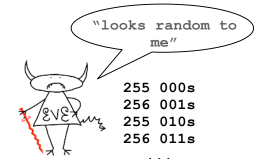


Linear Feedback Shift Register Demo

0	1	1	0	1	0	0	0	0	1	0	Time 0
1	1	0	1	0	0	0	0	1	0	1	Time 1
1	0	1	0	0	0	0	1	0	1	1	Time 2
0	1	0	0	0	0	1	0	1	1	0	Time 3
1	0	0	0	0	1	0	1	1	0	0	Time 4
0	0	0	0	1	0	1	1	0	0	1	Time 5
0	0	0	1	0	1	1	0	0	1	0	Time 6
0	0	1	0	1	1	0	0	1	0	0	Time 7
0	1	0	1	1	0	0	1	0	0	1	Time 8

Random Numbers

Q. Are these 2000 numbers random?
If not, what is the pattern?



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

```
1100100100111101101110010110101110011000101111110100100001001101001011110011001001111111011100
0001010110001000011101010011010000111100100110011101111111010100000100001000101001010100011000
0010111100010010011010110111100011010011011100111101011110010001001110101011101000001010010001
0001101010101110000000101100000100111000101110110100101011001100001111111001100000111111000110
0001101111001110100111101001110010011101110111010101010100000000000100000000101000000100010000 1
0101010010000000110100000111001000110111010111010100010100001010001001000101011010100001100001
0011110010111001110010111101110010010101110110000101011100100001011101001001010011011000111101
1101100101010111100000001001100001011111001001000111011010110101100011000111011110110101001011 0
0001100111001111110111100001010011001000111111010110000100011100101011011100001101011001110001
1111011011000101101110100110101001111000011100110011011111111101000000010010000010110100010011
0010101111110000100001100101001111100011100011011011011101101101010110110000011011100011101011
0110100011011001011101111001010100111000001110110001101011101110001010101101000000110010000111
1101001100010011111010111000100010110101010011000000111110000110001100111101111110010100001110
0010011011010111101100010010111010110010100011110001011001101001111110011100001111011001100101
1111111001000000111010000110100100111001101110111101010100010000001010100001000001001010001 01
1000101001110100011101001011010011001100111111111110000000001100000001111000001100110001111111
1011000000101110000100101100101100111100111110011110001111001101100111110111110001010001101000
1011100101001011100011001011011111001101000111110010110001110011101101111010110100100011001101
0111111100010000011010100011100001011011001001101111011110100101001001100011011111011101000101
0100101000000110001000111101010110010000011110100011001001011111011001000101111010100100100001 1
0110100111011001110101111101000100010010101010110000000011100000011011000011101110011010101111
1000001000110001010111 1010
```

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
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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

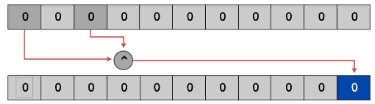
char	dec	binary
A	0	000000
B	1	000001
…	…	…
M	12	001100
…	…	…

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.

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



```
Ex: (1, 2) LFSR
001
010
101
011
111
110
100
001  2³-1 = 7
```

Property 2: Bitstream must eventually cycle.

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

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)

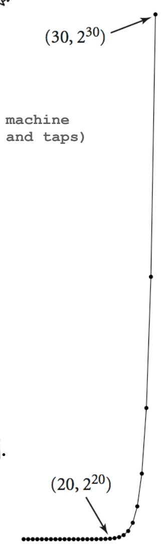
- Seeds are short, messages are long.
- All seeds give a tiny fraction of all messages.
- Extremely likely that all but real seed will produce gibberish.

Bad news (for Eve): Alice and Bob can use a much larger LFSR.

- For instance: 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]

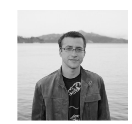
- Experts have cracked LFSR encryption.

  [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.



DVD Jon
(Norwegian hacker)

```
/*     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

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 final int tap;
   private final 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.print(lfsr.step());
   }
}
```

```
% java LFSR
11001001001111011011100101101011
11001100010111111010010000100011
01001011110011001001111...
```