COS 126

General Computer Science
Fall 2009

Robert Sedgewick

Overview

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

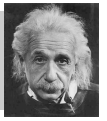
Goals.

- 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*



The Basics

Lectures. [Prof. Sedgewick]

- Tuesdays and Thursdays 10AM, McCosh 10.
- Office hours: W 12-2pm in CS 316 or CS tea room. ← everyone needs to meet me!

Precepts. [Donna Gabai (co-lead) · Maia Ginsburg (co-lead) · Aleksey Boyko · Jesse Farnham · Tom Funkhouser · Rob Harrison · Timothy Lee · Jen Rexford · David Shue · Aaron Wong]

- Tue+Thu or Wed+Fri.
- Tips on assignments, worked examples, clarify lecture material.
- Informal and interactive.

Friend 016/017 lab. [Undergrad lab assistants]

- Sun-Fri 7-11pm, Sat 2-6pm.
- Help with systems/debugging.

Full details and preceptor office hours. See `www.princeton.edu/~cos126`

Grades

Course grades. No preset curve or quota.

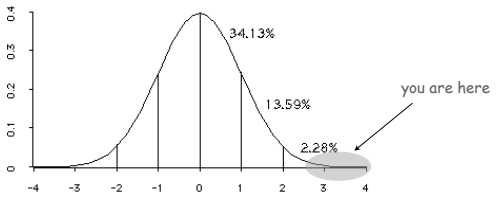
9 programming assignments. 40%.

2 exams. 50%.

Final programming project. 10%.

Extra credit and staff discretion. Adjust borderline cases.

↖ participation helps, frequent absences hurts



Course Materials

Course website. [www.princeton.edu/~cos126]

- Submit assignments, check grades.
- Programming assignments.
- Lecture slides.

print before lecture; annotate during lecture

skim before lecture; read thoroughly afterwards

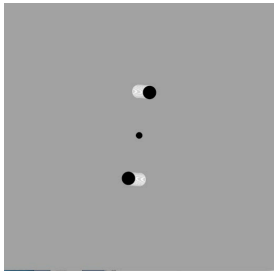
Required readings. Sedgewick and Wayne. Intro to Programming in Java: An Interdisciplinary Approach. [Labyrinth]

Recommended readings. Harel. What computers can't do. [Labyrinth]

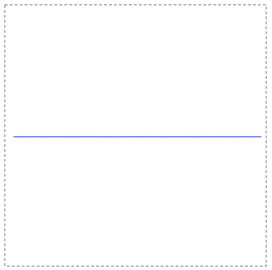
Programming Assignments

Desiderata.

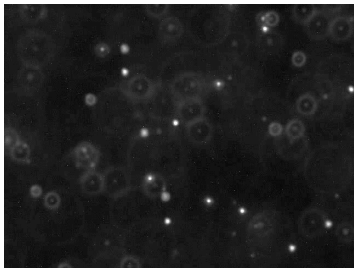
- Address an important scientific or commercial problem.
- Illustrate the importance of a fundamental CS concept.
- You solve problem from scratch!



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 11pm 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 Donna O'Leary in CS 210 if the only precept you can attend is closed

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

- Due Monday 11PM.
- Read Sections 1.1 and 1.2 in textbook.
- Install Java programming environment + a few exercises.
- Lots of help available, don't be bashful.

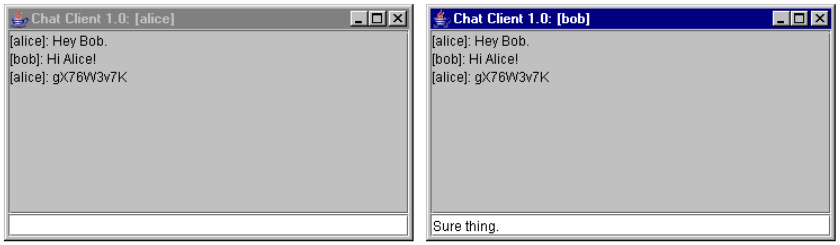
END OF ADMINISTRATIVE STUFF

0. Prologue: A Simple Machine

Secure Chat

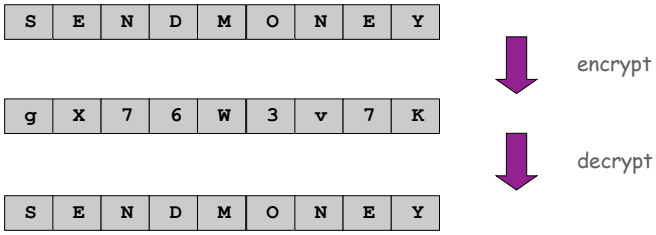
Alice wants to send a secret message to Bob?

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



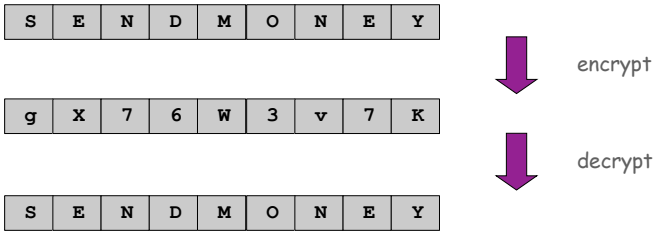
Encryption Machine

Goal. Design a machine to encrypt and decrypt data.



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]

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

File formats. txt, pdf, java, exe, docx, ppt, jpeg, mp3, divx, …

computer with
a lens

computer with
earbuds

computer with
a radio

A Digital World

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

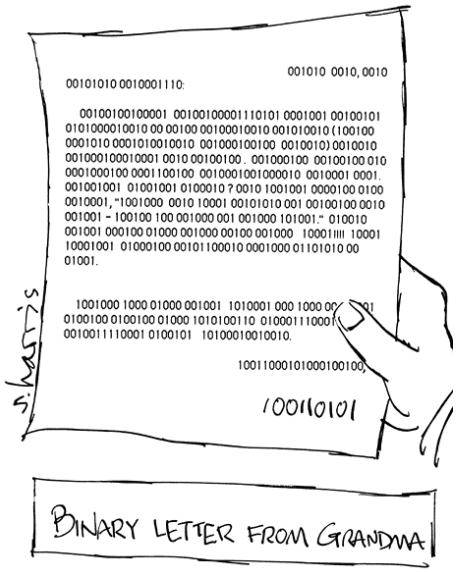
- Text.
- Programs, executables.
- Documents, pictures, sounds, movies, …

File formats. txt, pdf, java, exe, docx, ppt, jpeg, mp3, divx, …

computer with
a cash dispenser

computer with
a ballot box

computer with
a heating element



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

3 Miles of Music

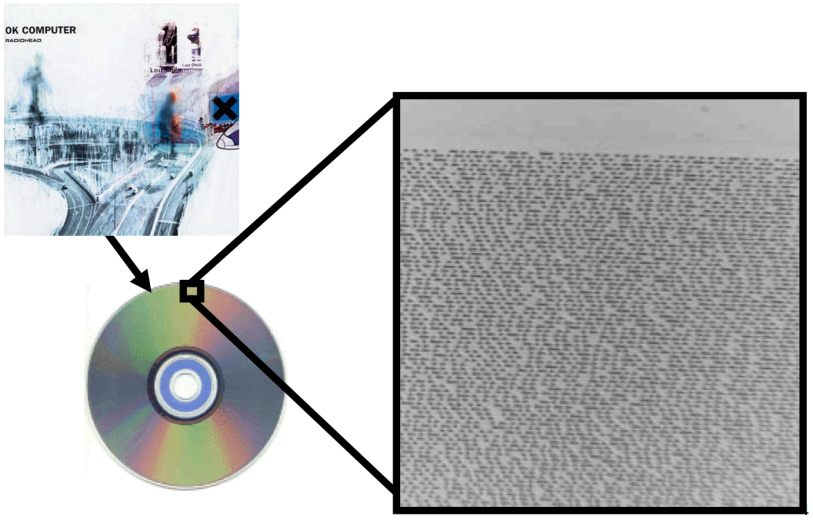


image courtesy of David August

A Digital World

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

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

Base64 encoding. Use 6 bits to represent each alphanumeric symbol.

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

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	
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	
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

Encryption.

- Convert text message to N bits.
- Generate N random bits (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	
010010	000100	001101	000011	001100	001110	001101	000100	011000	base64
110010	010011	110110	111001	011010	111001	100010	111111	010010	random bits
100000	010111	111011	111010	010110	110111	101111	111011	001010	XOR

0 ^ 1 = 1

One-Time Pad Encryption

Encryption.

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

Base64 Encoding

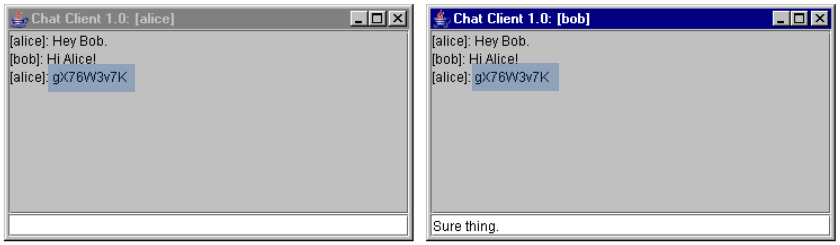
char	dec	binary
A	0	000000
B	1	000001
…	…	…
w	22	010110
…	…	…

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	random bits
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
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	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
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	random bits
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
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	random bits
010010	000100	001101	000011	001100	001110	001101	000100	011000	XOR
S	E	N	D	M	O	N	E	Y	message

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
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

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]

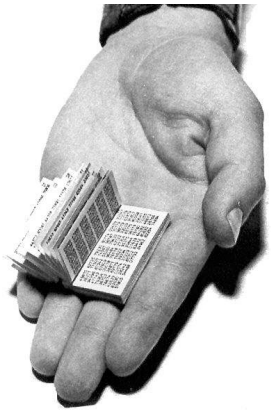
eavesdropper Eve sees only random bits

"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.

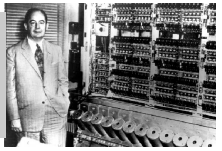
- Make a pseudo-random bit generator gadget.
- Alice and Bob each get identical small gadgets.

instead of identical large one-time pads

How to make small gadget that produces pseudo-random numbers.

- Linear feedback shift register.
- Linear congruential generator.
- Blum-Blum-Shub generator.
- ...

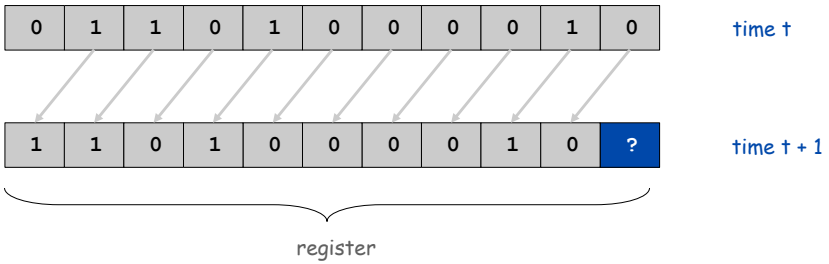
" Anyone who considers arithmetical methods of producing random digits is, of course, in a state of sin. "
– Jon von Neumann (left)
– ENIAC (right)



Shift Register

Shift register terminology.

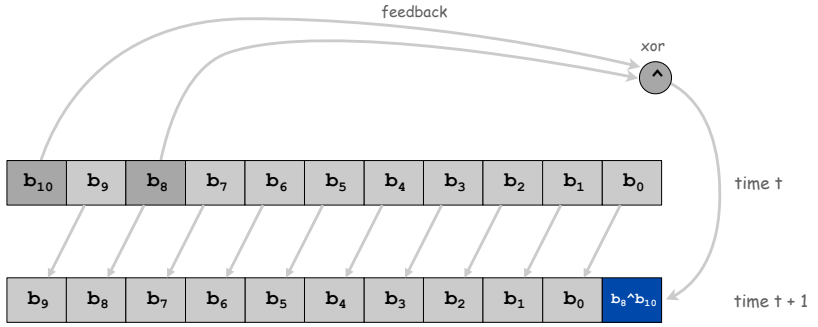
- Bit: 0 or 1.
- Cell: storage element that holds one bit.
- Register: sequence of cells.
- Seed: initial sequence of bits.
- Shift register: when clock ticks, bits propagate one position to left.



Linear Feedback Shift Register (LFSR)

{8, 10} linear feedback shift register.

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



Random Numbers

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

```
11001001001111011011100101101011100110001011111101001000010011010010111100110010011111111011100
00010101100010000111010100110100001111000100110011101111111101010000100001000101001010100011000
00101111000100100110101101101111000110100110111001111010111001000100011101010111010000010100100
00011010101011100000001011000001001110001011101101001010110011000011111110011000001111110001100
00011011110011101001111010011100100111011101110101010100000000010000000101000000100010000100001
01010100100000001101000001110010001101110101110101000101000010100010010001010110101000011000001
00111100101110011100101111011100100101011101100001010111001000010111010010010100111001100111101
11011001010101111000000100110000101111100100100011101101101101100011000111011101101010010101010
00011001110011111110111100001010011001000111111010110000010001110010101011011100001101011001110001
11110110110001011011101001101010011110000111001100110111111111010000000100100000101101000100011
00101011111100001000011001010011111000111000110110101101110110110101101011011000001101110001110101
01101000110110010111011110010101001110000011101100010110111011000010101011010000001100100001111
11010011000100111110101110001000101101010100110000001111100001100011001111011111100101000011100
00100110110101110111000100101110101100101000111000101100110100111111001110000111101100110010100
11111110010000001110100001101001100110111011111010100010000001010100001000001001010001000010100101
10001010011101000111010010110100110011001111111111100000000011000000111100000110011000111111100
10110000001011100001001011001011001111001111000111001101110011111011111001010001100011101000100
10111001010010111000110010110111110011010001111100101100011100111011011101011010010001100110100
01111111000100000110101000111000010110110010011011101111010010100100110001101111101101001000101
01001010000011000100011110101011001000011110100110010010111110110010001011110101001001000011000
01101001110110011101011111010001000100101010101100000000111000000110110000111011100110101011111
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 small key
- 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 small key
- 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

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.

Bad.

- Easily breakable if key is re-used.
- Still need secure, independent key distribution.
- Truly random bits are very hard to come by.

a commercially available LFSR

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

LFSR Challenge 1

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

Challenge. Can we 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.

LFSR Challenge 2

Goal. Decrypt/encrypt 1 gigabyte (2^{33} bits) movie.

Challenge. How big an LFSR?

A. 33 bits should be enough.

B. 100 bits is safe.

C. 1,000 bits is definitely secure.

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
11001001001111011011100101101011
11001100010111111010010000100110
01001011110011001001111...
```


A Profound Question

Q. What is a random number?

LFSR does not produce random numbers.

- It is a very simple deterministic machine.
- But not obvious how to distinguish the bits it produces from random.

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