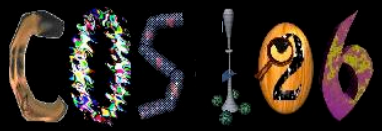


General Computer Science †
Princeton University
Fall 2006

Douglas Clark

† Some lectures overlap with CHM/COS/MOL/PHY 231/2

Overview

What is COS 126?

- Broad, but technical, intro to CS in the context of scientific, engineering, and commercial applications.
- No prerequisites, intended for novices.

Goals.

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

Topics.

- Programming in Java.
- Machine architecture.
- Theory of computation.
- Applications.

The Usual Suspects

Lectures. [Doug Clark]

- Tuesdays and Thursdays, Friend 101.

Precepts. [Ari Feldman, Maia Ginsburg, Nadia Heninger, Elliott Karpilovsky, Tim O'Connor, Vivek Pai, George Reis, Adam Stoler]

- COS 126: Tue+Thu or Wed+Fri.
- CHM/COS/MOL/PHY 231/2: Wed or Th.
  - Special precept today, 2:30, Lewis Thomas Lab 012
- Tips on assignments, worked examples, clarify lecture material.

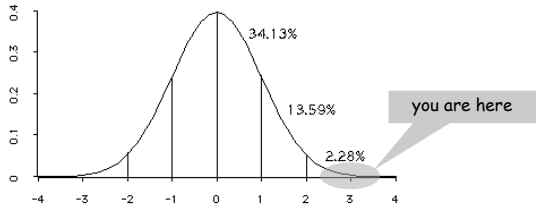
Friend 016/017 lab. [Undergrad lab assistants.]

- Weekdays 7-11pm, some weekend hours.
- Full schedule to be posted on Web.

Grades

Course grades. No preset curve or quota.

Programming assignments. 35%.
2 exams. 50%. ← can drop lowest one
Final programming project. 15%.
Staff discretion and extra credit. Adjust borderline cases.



Course Materials

Course website. [www.princeton.edu/~cos126]
- Programming assignments.
- Lecture notes.
- Submit assignments, check grades.

Required readings.
- Sedgewick and Wayne. *Intro to Programing.* [U-Store]
  - Available tomorrow
  - booksite [www.cs.princeton.edu/IntroCS]

Recommended readings.
- Harel. *What computers can't do.* [U-Store]

Programming Assignments

Desiderata.
- Address an important scientific or commercial problem.
- Illustrate the importance of a fundamental CS concept.

Examples.
- N-body simulation.
- DNA sequence alignment.
- Digital signal processing of MP3 files.
- Traveling salesperson problem.
- Markov model of natural language.

} you solve scientific problems from scratch!

Due. (Usually) Mondays 11:55pm via Web submission.

Computing equipment.
- Your machine. [Linux, OS X, Windows, Java cell phone, …]
- OIT machines. [Friend 016 and 017 labs]

What's Ahead?

Thursday. CHM/COS/MOL/PHY 231/2 meets in LTL 012 2:30.

Thursday or Friday. COS 126 precepts meet.
- Don't know yours? Check the printout or website.
- See Maia Ginsburg after class if not registered.

ASAP! Read sections 1.1 – 1.2 of Intro to Programming.

Due Monday. Assignment 0.
- Setup Java programming environment.
- Lots of help available, don't be bashful.

Tuesday. Lecture 2: Introduction to Java.

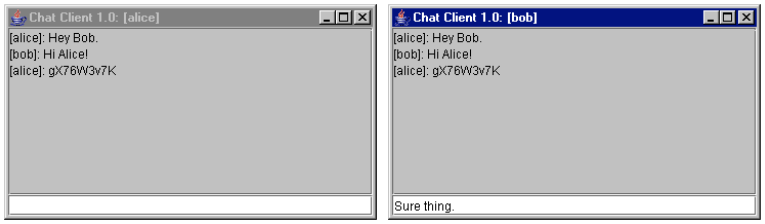
END OF ADMINISTRATIVE STUFF

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

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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.

Digital Data

Computers store all data as a sequence of bits.

- Text.
- Images (JPEG), audio (MP3), video (DivX).
- Programs.

0 or 1

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.

0 or 1

Base64 Encoding

char	dec	binary
A	0	000000
B	1	000001
...	...	...
Y	24	011000
...	...	...

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 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

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
...	...	...
X	23	010111
...	...	...

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
g	X	7	6	W	3	v	7	K	encrypted

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
...	...	...
X	23	010111
...	...	...

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

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Decryption.

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110010	010011	110110	111001	011010	111001	100010	111111	010010	random bits
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
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...	...	...

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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?

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

Crucial property. Decrypted message = original message.

Why is crucial property true?

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

associativity of ^ | always 0 | identity

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

Goods and Bads of One-Time Pads

Good.

- Very simple encryption/decryption processes.
- Provably unbreakable if pad is truly random. [Shannon, 1940s]

Bad.

"one time" means one time only

- 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

Pseudo-Random Number Generator

Practical middle-ground.

- Let's make a pseudo-random bit generator gadget.
- Alice and Bob each get identical small gadgets instead of identical large one-time pads.

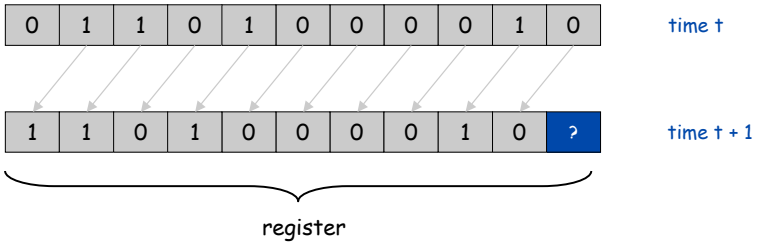
How to make small gadget that produces "random" numbers.

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

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.

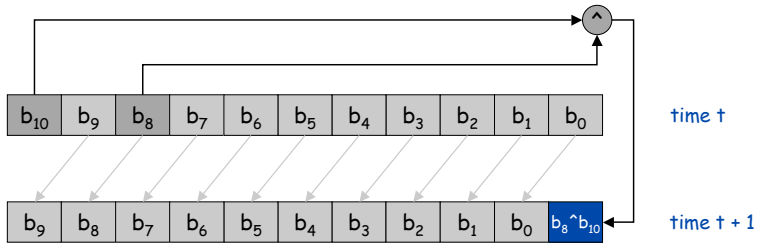


Linear Feedback Shift Register

{8, 10} linear feedback shift register.

- 11 bit shift register.
- New output bit 0 is XOR of previous bits 8 and 10.
- Output bit = bit 0.

LFSR demo



Random Numbers

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

```
11001001001111011011100101101011100110001011111101001000010011010010111100110010011111
10111000001010110001000011101010011010000111100100110011101111111010100001000010001010
01010100011000001011110001001001101101111000110100110111001111010111100100001001110101
01110100000101001000100011010101011100000001011000001001110001011101101001010110011000
11111110011000001111110001100001101111001110100111010011100100111011101010101001000
00000001000000001010000001000100001010101001000000011010000011100100011011101011010100
01010000101000100100010101101010000110000100111100101110011100101111011001001010111011
00001010111001000010111010010010011011000111101110110010101011110000001001100001101111
10010010001110110101101011000110001110111101101010010110000110011100111111011110000101
01100100011111101011000010001110010101101110000110101100111000111110110100010110111010
01101010011110000111001100101111111110100000001001000001011010001001100101011111100001
00001100101001111100011000110110110111011011010101101100000110111000111010110110100011
01100101111011111001010100111000001110110001101011101110001010101101000000110010000111110
10011000100111110101110001000101101010100110000001111100001100011001111011111110010100000
11100010011010101111011000100101110101100101000111100010110011010011111100111000011110
11001100101111111100100000011101000011010010011100110111011111010101000100000010101000
10000010010100010110001010011101000111010010110100110011001111111111100000000110000000
11110000011001100011111111011000000101110000100101100101100111100111110011100111100011110011
01100111101111100010100011010001011100101001011100011001011011111001101000111100101100
00111001110110111010110100100011001101011111100010000011010100011100001011011001001100
11110111101001010010011000110111110111010001010100101000001100010001111010101100100000
11101000110010010111110110010001011110101001001000011011010011100111010111110010000100
01001010101011000000001110000001101100001110111001101010111110000010001100010101111010
```

A. No. This is output of an 11 bit LFSR!

The Science Behind A LFSR

Q. Are the bits really random?
A. No! Real machines are deterministic.

Q. Will bit pattern repeat itself?
A. Yes, after $2^{11} - 1 = 2047$ steps.

Q. What if I need more bits?
A. Scalable: 20 cells for 1 million bits, 30 for 1 billion.

Q. Will the machine work equally well if we XOR bits 4 and 10?
A. No! Need to understand theory of finite groups.

Q. How many cells do I need to guarantee a certain level of security?
A. Subject of active research.

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
                               ;})
```

Reference: 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.

Simulating The Abstract Machine in Java

Java program prints same bits as LFSR.

- You'll understand this program by next week.

```
public class LFSR {
   public static void main(String[] args) {
      int N = Integer.parseInt(args[0]);
      boolean b10 = false, b9 = true,  b8 = true,  b7 = false;
      boolean b6  = true,  b5 = false, b4 = false, b3 = false;
      boolean b2  = false, b1 = true,  b0 = false;

      for (int i = 0; i < N; i++) {                    repeat N times
         boolean bit = b8 ^ b10;
         b10 = b9; b9 = b8; b8 = b7; b7 = b6; b6 = b5;
         b5  = b4; b4 = b3; b3 = b2; b2 = b1; b1 = b0;
         b0 = bit;                                     update

         if (bit) System.out.print(1);                 print
         else     System.out.print(0);
      }
   }
}
```

```
% java LFSR 2000
11001001001111011011001011010111001100010111111010010000100110100101111001100100111...
```