Cryptography

Lecture 23

Announcements

- HW5 due on Wednesday, 4/24

Agenda

- Last time:
  - Cyclic groups
- This time:
  - More on Cyclic Groups
  - Hard problems (Discrete log, Diffie-Hellman Problems—CDH, DDH)
  - Elliptic Curve Groups

Cyclic Groups

For a finite group G of order m and $g \in G$, consider:

$$\langle g \rangle = \{g^0, g^1, \dots, g^{m-1}\}$$

$\langle g \rangle$ always forms a cyclic subgroup of G.

However, it is possible that there are repeats in the above list.

Thus $\langle g \rangle$ may be a subgroup of order smaller than m.

If $\langle g \rangle = G$, then we say that G is a cyclic group and that g is a generator of G.

Examples

Consider $Z^*{}_{13}$:

2 is a generator of $Z^*{}_{13}$:

2^0	1
2^1	2
2^2	4
2^3	8
2^4	$16 \to 3$
2^5	6
2^6	12
2^7	$24 \to 11$
2^8	$22 \to 9$
2^9	$18 \to 5$
2^{10}	10
2^{11}	$20 \to 7$
2^{12}	$14 \to 1$

order of 2 is 12

3 is not a generator of $Z^*{}_{13}$:

3^0	1
3^1	3
3^2	9
3^3	$27 \to 1$
3^4	3
3^5	9
3^6	$27 \to 1$
3^7	3
3^8	9
3^9	$27 \to 1$
3^{10}	3
3^{11}	9
3^{12}	$27 \to 1$

order of 3 is 3

Definitions and Theorems

Definition: Let G be a finite group and $g \in G$. The order of g is the smallest positive integer i such that $g^i = 1$.

Ex: Consider Z_{13}^*. The order of 2 is 12. The order of 3 is 3.

Proposition 1: Let G be a finite group and $g \in G$ an element of order i. Then for any integer x, we have $g^x = g^{x \bmod i}$.

Proposition 2: Let G be a finite group and $g \in G$ an element of order i. Then $g^x = g^y$ iff $x \equiv y \bmod i$.

G

Cyclic group of order q

generator g

$$\boxed{(G, q, g)}$$

Adv		**Chall**
	$\{0, \ldots, q-1\}$
	$x \xleftarrow{R} \mathbb{Z}_q$
$\xleftarrow{\quad y \quad}$	$g^x = \boxed{y}$
trying to compute $\mathrm{Dlog}_g(y)$	$\xrightarrow{\quad z \quad}$

More Theorems

Proposition 3: Let G be a finite group of order m and $g \in G$ an element of order i. $\boxed{\text{Then } i \mid m.}$

Proof:

- We know by the generalized theorem of last class that $\boxed{g^m = 1 = g^0}$.
- By Proposition 2, we have that $0 \equiv m \bmod i$
- By definition of modulus, this means that $i|m$.

Corollary: if G is a group of prime order p, then G is cyclic and all elements of G except the identity are generators of G.

Goal: Construct prime order cyclic group.

Why does this follow from Proposition 3?

Theorem: If p is prime then $\boxed{Z^*_p}$ is a cyclic group of order $\boxed{p-1}$.

Prime-Order Cyclic Groups

Consider $Z^*{}_p$, where $\boxed{p \text{ is a strong prime.}}$

- Strong prime: $p = 2q + 1$, where q is also prime.
- Recall that $Z^*{}_p$ is a cyclic group of order $p - 1 = 2q$.

perfect squares

The subgroup of $\boxed{\text{quadratic residues}}$ in $Z^*{}_p$ is a cyclic group of prime order q.

Example of Prime-Order Cyclic Group

$\mathbb{Z}^*_p$

Consider $Z^*{}_{11}$.

Note that 11 is a strong prime, since $\boxed{11 = 2 \cdot 5 + 1.}$

$g = 2$ is a generator of $Z^*{}_{11}$:

~~ECDH~~

2^0	1
2^1	2
2^2	4
2^3	8
2^4	$16 \to 5$
2^5	10
2^6	$20 \to 9$
2^7	$18 \to 7$
2^8	$14 \to 3$
2^9	6

The even powers of g are the "quadratic residues" (i.e. the perfect squares). Exactly half the elements of $Z^*{}_p$ are quadratic residues.

Note that the even powers of g form a cyclic subgroup of order $\frac{p-1}{2} = q$.

inverse

Verify:

- closure (Multiplication translates into addition in the exponent. Addition of two even numbers mod $p - 2$ gives an even number mod $p - 1$, since for prime $p > 3$, $p - 1$ is even.)
- Cyclic –any element is a generator. E.g. it is easy to see that all even powers of g can be generated by g^2.

The Discrete Logarithm Problem

The discrete-log experiment $DLog_{A,\boldsymbol{G}}(n)$

1. Run $\boldsymbol{G}(1^n)$ to obtain (G, q, g) where G is a cyclic group of order q (with $||q|| = n$) and g is a generator of G.
2. Choose a uniform $h \in G$
3. A is given G, q, g, h and outputs $x \in Z_q$
4. The output of the experiment is defined to be 1 if $g^x = h$ and 0 otherwise.

Definition: We say that the DL problem is hard relative to $\boldsymbol{G}$ if for all ppt algorithms A there exists a negligible function neg such that

$$\Pr\left[DLog_{A,\boldsymbol{G}}(n) = 1\right] \leq neg(n).$$

The Diffie-Hellman Problems

Computational

The CDH Problem

Adv $\boxed{G, q, g}$ Chall

$x_1, x_2 \leftarrow \mathbb{Z}_q$

$\xleftarrow{h_1, h_2}$

$h_1 = g^{x_1}$,

$h_2 = g^{x_2}$

$z = g^{x_1 \cdot x_2}$ $\xrightarrow{z}$

public

Given (G, q, g) and uniform $h_1 = g^{x_1}, h_2 = g^{x_2}$, compute $g^{x_1 \cdot x_2}$.

$\mathrm{Dlog}_g(h_1) = x_1$

$\left(h_2^{\,x_1} \right)$

The CDH Assumption $\longrightarrow$ The Dlog assumption

If you can break DLog $\longrightarrow$ You can break CDH

Decisional

The DDH Problem

We say that the DDH problem is hard relative to $\boldsymbol{G}$ if for all ppt algorithms A, there exists a negligible function neg such that

$$|\Pr[A(G, q, g, g^x, g^y, g^z) = 1] - \Pr[A(G, q, g, g^x, g^y, g^{xy}) = 1]| \leq neg(n).$$

Ideal

$x, y, z \leftarrow \mathbb{Z}_q$ (g^x, g^y, g^z)

Real

$x, y \xleftarrow{R} \mathbb{Z}_q$

$(g^x, g^y, g^{x \cdot y})$

D

can modify this attack for any non-prime order group

The DDH problem is <u>not</u> hard in $\mathbb{Z}_p^*$

$\boxed{\text{Legendre Symbol}}$ a poly-time algorithm to check whether $z \in \mathbb{Z}_p^*$ is a quadratic residue or not

quadratic residues are elements g^a a is even.

$D\log_g(z)$ is even or odd

(g^x, g^y, g^z) vs $(g^x, g^y, g^{x \cdot y})$

	g^x	g^y	g^z		g^x	g^y	$g^{x \cdot y}$	
any pattern	0	0	0		1	1	0	X
	0	0	1		1	0	1	X
	0	1	0					
	⋮							

& Fill in details of distinguishing attack

Relative Hardness of the Assumptions

$\xleftarrow{?}$ $\quad\quad$ $\not\leftarrow$?

candidate grp's where DDH is broken, CDH believed hard

Breaking DLog → Breaking CDH → Breaking DDH

DDH Assumption → CDH Assumption → DLog Assumption

$$(\boxed{g^x, g^y}, \underbrace{g^z}) \text{ vs. } (\boxed{g^x, g^y}, \underbrace{g^{xy}})$$

(Finite) Fields:

Elliptic Curve Groups

$\mathbb{Z}^*_p$

- A (finite) set of elements that can be viewed as a group with respect to two operations (denoted by addition and multiplication).

$\mathbb{Z}_p$

- The identity element for addition (0) is not required to have a multiplicative inverse.
- Example: Z_p, for prime p: {0, ..., p-1}
  - Z_p is a group with respect to addition mod p
  - Z*_p (taking out 0) is a group with respect to multiplication mod p
- We can now consider *polynomials* over Z_p as polynomials consist of only multiplication and addition.

Elliptic Curves over Finite Fields

- Z_p is a finite field for prime p.
- Let $p \geq 5$ be a prime
- Consider equation E in variables x, y of the form:

$$\boxed{y^2 := x^3 + Ax + B} \; mod\ p$$

Where A, B are constants such that $4A^3 + 27B^2 \neq 0$.
(this ensures that $x^3 + Ax + B\ mod\ p$ has no repeated roots).

Let $E(Z_p)$ denote the set of pairs $(\boxed{x, y}) \in Z_p \times Z_p$ satisfying the above equation as well as a special value O. point at infinity

$$E(Z_p) := \{(x, y) | x, y \in Z_p \text{ and } y^2 = x^3 + Ax + B\ mod\ p\} \cup \{O\}$$

The elements $E(Z_p)$ are called the points on the Elliptic Curve E and O is called the point at infinity.

Elliptic Curves over Finite Fields

$p = 7$

$0 \to 0$
$1 \to 1, 6$
$4 \to 2, 5$
$2 \to 3, 4$

Example:

Quadratic Residues over Z_7.

$0^2 = \boxed{0}, 1^2 = \boxed{1}, 2^2 = \boxed{4}, 3^2 = 9 = \boxed{2}, 4^2 = 16 = 2, 5^2 = 25 = 4, 6^2 = 36 = 1.$

$f(x) := \boxed{x^3 + 3x + 3}$ and curve $E : y^2 = f(x) \; mod \; 7$.

- Each value of x for which $f(x)$ is a non-zero quadratic residue mod 7 yields 2 points on the curve
- Values of x for which $f(x)$ is a non-quadratic residue are not on the curve.
- Values of x for which $f(x) \equiv 0 \; mod \; 7$ give one point on the curve.

$f'(x) = x^3 + 3x + 3$ $\mathbb{Z}_7$

Elliptic Curves over Finite Fields

$f(0) \equiv 3 \; mod \; 7$	a quadratic non-residue mod 7
$f(1) \equiv 0 \; mod \; 7$	so we obtain the point $(1,0) \in E(Z_7)$
$f(2) \equiv 3 \; mod \; 7$	a quadratic non-residue mod 7
$f(3) \equiv 4 \; mod \; 7$	a quadratic residue with roots $2,5$. so we obtain the points $(3,2), (3,5) \in E(Z_7)$
$f(4) \equiv 2 \; mod \; 7$	a quadratic residue with roots $3,4$. so we obtain the points $(4,3), (4,4) \in E(Z_7)$
$f(5) \equiv 3 \; mod \; 7$	a quadratic non-residue mod 7
$f(6) \equiv 6 \; mod \; 7$	a quadratic non-residue mod 7

1
2
2
+
$\mathcal{O}$

Elliptic Curves over Finite Fields

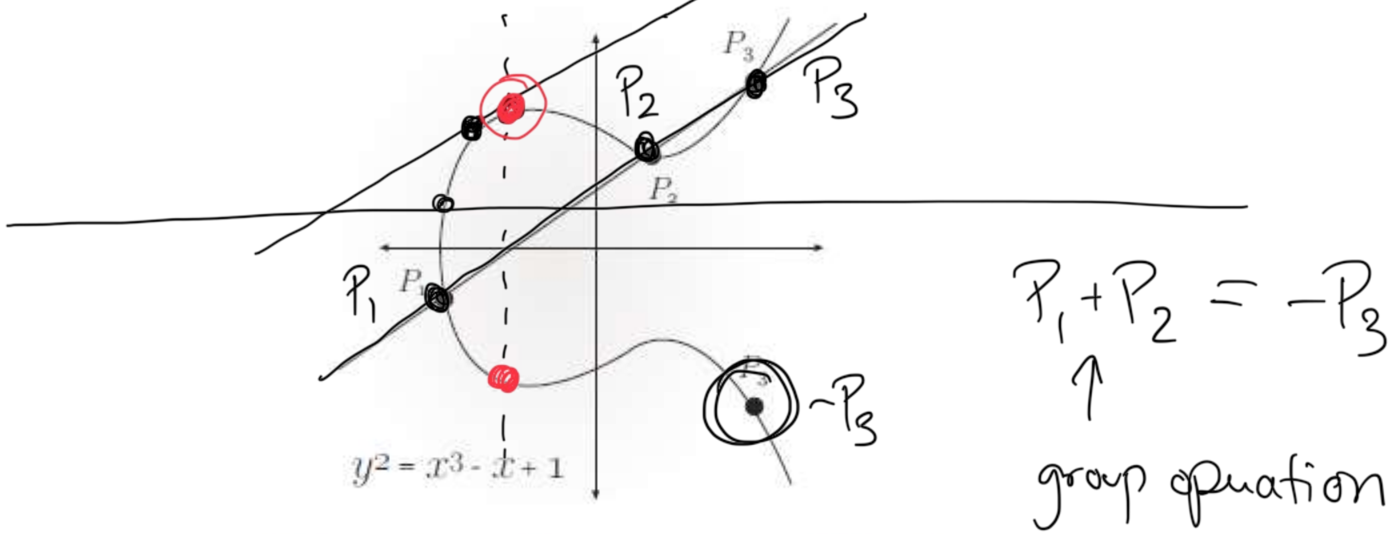


FIGURE 8.2: An elliptic curve over the reals.

Point at infinity: O sits at the top of the y-axis and lies on every vertical line.

Every line intersecting $E(Z_p)$ in 2 points, intersects it in exactly 3 points:

1. A point P is counted 2 times if line is tangent to the curve at P.
2. The point at infinity is also counted when the line is vertical.

Addition over Elliptic Curves

Binary operation "addition" denoted by $+$ on points of $E(Z_p)$.

- The point O is defined to be an additive identity for all $P \in E(Z_p)$ we define $P + O = O + P = P$. ✓
- For 2 points $P_1, P_2 \neq O$ on E, we evaluate their sum $P_1 + P_2$ by drawing the line through P_1, P_2 (If $P_1 = P_2$, draw the line tangent to the curve at P_1) and finding the 3rd point of intersection P_3 of this line with $E(Z_p)$.
- The 3rd point may be $P_3 = O$ if the line is vertical.
- If $P_3 = (x, y) \neq O$ then we define $P_1 + P_2 = (x, -y)$.
- If $P_3 = O$ then we define $P_1 + P_2 = O$.

Additive Inverse over Elliptic Curves

- If $P = (x, y) \neq O$ is a point of $E(Z_p)$ then $-P = (x, -y)$ which is clearly also a point on $E(Z_p)$.
- The line through $(x, y), (x, -y)$ is vertical and so addition implies that $P + (-P) = O$.
- Additionally, $\boxed{-O = O.}$

Groups over Elliptic Curves

Proposition: Let $p \geq 5$ be prime and let E be the elliptic curve given by $y^2 = x^3 + Ax + B \bmod p$ where $4A^3 + 27B^2 \neq 0 \bmod p$.

Let $P_1, P_2 \neq O$ be points on E with $P_1 = (x_1, y_1)$ and $P_2 = (x_2, y_2)$.

1. If $x_1 \neq x_2$ then $P_1 + P_2 = (x_3, y_3)$ with
$$x_3 = [m^2 - x_1 - x_2 \bmod p], y_3 = [m - (x_1 - x_3) - y_1 \bmod p]$$
Where $m = \left[\frac{y_2 - y_1}{x_2 - x_1} \bmod p\right]$.
2. If $x_1 = x_2$ but $y_1 \neq y_2$ then $P_1 = -P_2$ and so $P_1 + P_2 = O$.
3. If $P_1 = P_2$ and $y_1 = 0$ then $P_1 + P_2 = 2P_1 = O$.
4. If $P_1 = P_2$ and $y_1 \neq 0$ then $P_1 + P_2 = 2P_1 = (x_3, y_3)$ with
$$x_3 = [m^2 - 2x_1 \bmod p], y_3 = [m - (x_1 - x_3) - y_1 \bmod p]$$
Where $m = \left[\frac{3x_1{}^2 + A}{2y_1} \bmod p\right]$.

The set $E(Z_p)$ along with the addition rule form an abelian group.
The elliptic curve group of E.

**Difficult property to verify is associativity. Can check through tedious calculation.

DDH over Elliptic Curves

DDH: Distinguish (aP, bP, abP) from (aP, bP, cP).

g^a

$\boxed{\text{additive}}$

exponential in p when p is the modulus.

much more compact + better when you want to save on communication

$\boxed{2^{128}}$

modulo p w/ 256 bits

$\mathbb{Z}_p^* - 2^{128}$ modulo p have to have 2048 bits

Size of Elliptic Curve Groups?

How large are EC groups $mod\ p$?

Heuristic: $y^2 = f(x)$ has 2 solutions whenever $f(x)$ is a quadratic residue and 1 solution when $f(x) = 0$.

Since half the elements of Z_p^* are quadratic residues, expect $\frac{2(p-1)}{2} + 1 = p$ points on curve. Including O, this gives $p + 1$ points.

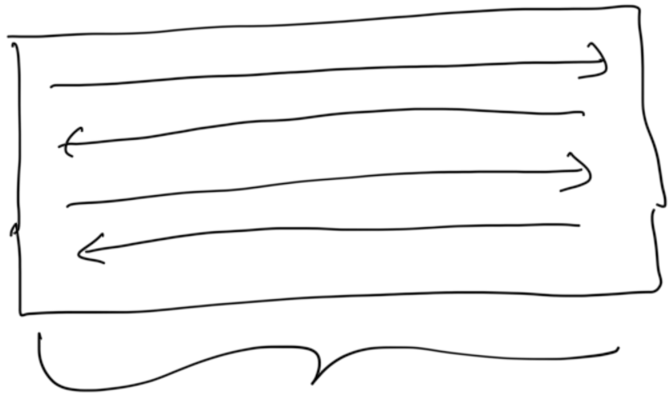
Theorem (Hasse bound): Let p be prime, and let E be an elliptic curve over Z_p. Then

$$p + 1 - 2\sqrt{p} \leq \left|E\left(Z_p\right)\right| \leq p + 1 + 2\sqrt{p}.$$

$\boxed{\text{Public Key Revolution}}$

Public Key Cryptography

Sender



Receiver

trans

K

$(Enc_K(m))$

$(m, Mac_K(m))$

K

$(trans, \hat{K})$

$\boxed{\text{Eve}}$

$(trans, K)$

This is the necessary def, to prove security of the $\frac{\text{composed}}{\text{interaction}}$

Key Agreement

The key-exchange experiment $KE^{eav}{}_{A,\Pi}(n)$:

1. Two parties holding 1^n execute protocol Π. This results in a transcript $trans$ containing all the messages sent by the parties, and a key $\boxed{k}$ output by each of the parties.
2. A uniform bit $b \in \{0,1\}$ is chosen. If $b = 0$ set $\hat{k} := \boxed{k}$, and if $b = 1$ then choose $\hat{k} \in \{0,1\}^n$ uniformly at random.
3. A is given $trans$ and $\hat{k}$, and outputs a bit b'.
4. The output of the experiment is defined to be 1 if $b' = b$ and 0 otherwise.

Definition: A key-exchange protocol Π is secure in the presence of an eavesdropper if for all ppt adversaries A there is a negligible function neg such that

$$\Pr\left[KE^{eav}{}_{A,\Pi}(n) = 1\right] \leq \frac{1}{2} + neg(n).$$