Cryptography

- **some history**
  - Caesar cipher, rot13
  - substitution ciphers, etc.
  - Enigma (Turing)

- **modern secret key cryptography**
  - DES, AES

- **public key cryptography**
  - RSA, digital signatures

- **cryptography in practice**

Cryptography basics

- **Alice & Bob want to exchange messages**
  - keeping the content secret
  - though not the fact that they are communicating
- **they need some kind of secret that scrambles messages**
  - makes them unintelligible to bad guys but intelligible to good guys
- **the secret is a "key" (like a password)**
  - known only to the communicating parties
  - that is used to do the scrambling and unscrambling
  - for Caesar cipher, the "key" is the amount of the shift (A => D, etc.)
  - for substitution ciphers, the key is the permutation of the alphabet
  - for Enigma, key is wiring and position of wheels plus settings of patches
  - for modern ciphers, the key is a large integer used as part of an intricate algorithmic operation on the bits of the message

Modern secret key cryptography

- **messages encrypted and decrypted with a shared secret key**
  - usually the same key for both operations ("symmetric")
- **encryption/decryption algorithm is known to adversaries**
  - "security by obscurity" *does not work*
- **attacks**
  - decrypt specific message(s) by analysis
    - various combinations of known or chosen plaintext and ciphertext
  - determine key by "brute force" (try all possible keys)
- **if key is compromised, all past and future messages are compromised**
- **big problem: key distribution**
  - need a secure way to get the key to both/all parties
    - diplomatic pouches, secret agents, ...
  - doesn't work when the parties don't know each other
  - or have no possible channel for exchanging a secret key
  - or when want to exchange secret messages with many different parties
    - e.g., credit card numbers on Internet

The secrecy is in the key

"Il faut qu'il n'exige pas le secret, et qu'il puisse sans inconvénient tomber entre les mains de l'ennemi."

(The system must not require secrecy, and it does not matter if it falls into the hands of the enemy.)

Auguste Kerckhoffs, "La cryptographie militaire",
Journal des sciences militaires, vol IX, pp 5-38, Jan 1883.

- **we have to assume that the bad guys know how the encryption and decryption operate**
- **“security by obscurity” does not work**

DES and AES

- **Data Encryption Standard (DES)**
  - developed ~1977 by IBM, with NSA involvement
  - widely used, though lingering concerns about trap doors
  - 56-bit key is now much too short:

    can exhaustively test all keys in a few hours

    with comparatively cheap special-purpose hardware
  - "triple DES" uses 3 DES encryptions to increase effective key length

- **Advanced Encryption Standard (AES)**
  - result of an international competition run by NIST (www.nist.gov/aes)
  - completely open: algorithms and analyses in public domain
  - Rijndael: winning algorithm selected October 2000

    approved as official US government standard
  - 128, 192, 256-bit keys
  - fast in both hardware and software implementations

The big problem: key distribution

- **we need a secure way to get the key to all parties**
  - diplomatic pouches, secret agents, steganography, …
- **doesn't work when there is no channel for exchanging a secret key**
- **or when two parties don't know each other**
- **or if we need to exchange secret messages with many different parties**
  - e.g., credit card numbers on Internet

Public key cryptography

- **fundamentally new idea**
  - Diffie & Hellman (USA, 1976); earlier in England but kept secret
- **each person has a public key and a private key**
  - the keys are mathematically related
  - a message encrypted with one can only be decrypted with the other
- **public keys are published, visible to everyone**
- **private keys are secret, known only to owner**

- **Alice sends a secret message to Bob by**
  - encrypting it with *Bob's* public key
  - only Bob can decrypt it, using his private key
- **Bob sends a secret reply to Alice by**
  - encrypting it with *Alice's* public key
  - only Alice can decrypt it, using her private key
- **Eve knows Alice and Bob are talking**
  - but can't decrypt what they are saying

RSA public key cryptographic algorithm

- **most widely used public key system**
- **invented by Ron Rivest, Adi Shamir, Len Adleman, 1977**
  - patent expired Sept 2000, now in public domain

- **based on (apparent) difficulty of factoring very large integers**
  - "large" >= 1024 bits ~ 300 digits
  - public key based on product of two large (secret) primes
  - encrypting and decrypting require knowledge of the factors
- **slow, so usually use RSA to exchange a secret "session key"**
  - session key used for secret key encryption with AES
  - used by SSH for secure login
  - used by browsers for secure exchange of credit card numbers

    https: http with encryption
  - SSL (Secure Sockets Layer) or TLS (Transport Layer Security)

    used to encrypt TCP/IP

How does RSA work? (you are not expected to remember this)

- **choose two big primes p and q (~100 digits each)**
- **compute $N = p \times q$ (~200 digits)**
- **select e, relatively prime to $(p-1) \times (q-1)$**
- **compute d such that $e \times d = 1 \bmod (p-1) \times (q-1)$**
- **public key is (e, N), private key is d**

- **to encode message m, $c = m^e \bmod N$**
- **to decode message c, $m = c^d \bmod N$**
- **decoding is easy if you know d, but hard if you don't:**
  - you have to figure out p-1 and q-1
  - so you have to figure out p and q
  - so you have to factor N
  - and that's too hard

A tiny example

- p = 17, q = 11 (primes)
- N = 17 × 11 = 187
- e = 7 (relatively prime to p-1 × q-1 = 16 × 10 = 160)
- d = 23 (7 × 23 = 161 = 1 mod 160)
- public key is (7, 187); private key is 23

- to encode “X” (88 in ascii),
  compute 88^7 mod 187 = 11

- to decrypt 11,
  compute 11^{23} mod 187 = 88

Digital signatures

- **can use public key cryptography for digital signatures**
  - if Alice encrypts a message with her <u>private</u> key
  - and it decodes properly with her public key
  - it had to be Alice who encoded it
- **signature can be attached to a message**
  - Alice encrypts a message with her private key
  - Alice encrypts the result with Bob's public key
  - only Bob can decrypt this (with his private key)
    but it won't make any sense yet
  - Bob then decrypts it with Alice's public key
  - if it decodes properly, it had to be Alice who encrypted it originally
- **necessary properties of digital signatures**
  - can only be done by the right person: can't be forged
  - can't re-use a signature to sign something else
  - signature attached to a document: signs specific contents
  - signature can't be repudiated

Secure hashes

- **digital signature usually done by signing a "secure hash" or "message digest" of a document, not the document itself**
- **secure hash algorithm reduces input data to a comparatively short number such that**
  - any change to the original document produces a completely different hash
  - can't deduce the original document from the number
  - can't find another document that has the same hash
- **current secure hash algorithms**
  - MD5 (Rivest, MIT): 128 bits
  - SHA-1 (US government standard): 160 bits
  - SHA-2 (also standard): family of 224, 256, 384, or 512 bits
- **international competition to create a new secure hash, SHA-3**
  - analogous to AES competition (also run by NIST)
  - first round submissions 10/08, final round 12/10,
  - winner announced in Oct 2012

Properties of public/private keys

- **can't deduce the public key from the private, or vice versa**
- **can't find another encryption key that works with the decryption key**
- **keys are long enough that brute force search is infeasible**

- **nasty problems:**
  - if a key is lost, all messages and signatures are lost
  - if a key is compromised, all messages and signatures are compromised
  - it's hard to revoke a key
  - it's hard to repudiate a key (and hard to distinguish that from revoking)

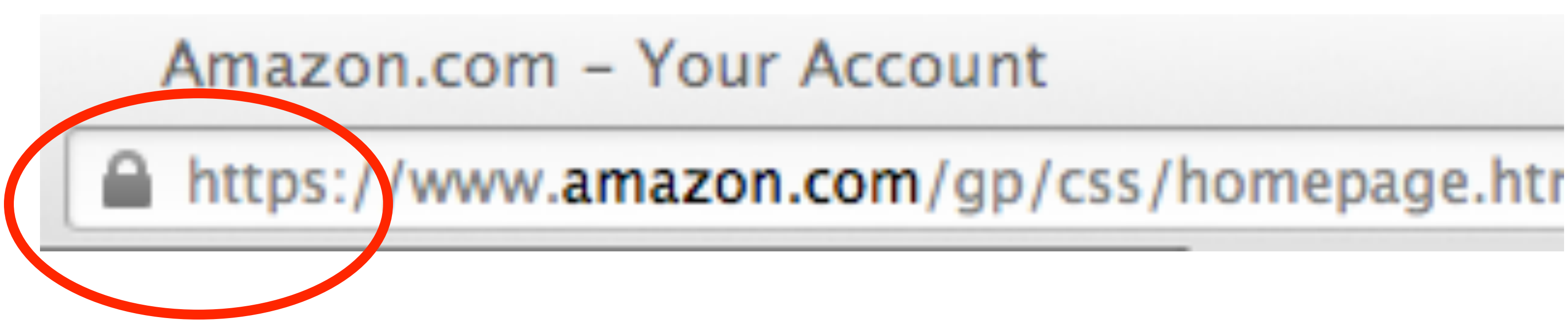
- **authentication**
  - how do you know who you are talking to? is that really Alice's public key?
  - public key infrastructure, web of trust, digital certificates

Encrypted transactions, online shopping

- **browser says "prove that you're really Amazon"**
- **Amazon says "here's my signed certificate from a CA"**
  - encrypted with the CA's private key
- **browser decrypts certificate with CA's public key**

- **browser generates a random key, encrypts it with Amazon's public key, sends it to Amazon**

- **browser and Amazon use AES to talk securely**



Tor: The Onion Router

- **anonymous routing through the Internet using TCP**
  - receiver can't determine the sender's address
- **sender creates a random path through a network of Tor relays**
  - path is changed frequently
- **each part of the path is encrypted**
  - separate encryption keys for each hop
- **each relay only knows who gave it data and who it sends data to**
  - no relay knows the whole path
- **messages are wrapped up with nested encryptions, one for each component of the path**
  - each relay removes one layer of encryption before passing on
- **potentially vulnerable to some attacks**
  - traffic correlation at end points
  - exit nodes can be blocked or monitored

Bitcoin digital currency (2009; see bitcoin.org et al)

- **exists only in digital form: nothing physical like gold**
  - no central authority or control
  - anonymous ownership and transfer
  - value fluctuates wildly
- **how are bitcoins created?**
- **how is ownership validated & transferred without double spending?**

- **block chain: shared public ledger of *all* transactions**
- **a transaction transfers value from one wallet to another**
  - signed digitally by the sender
  - broadcast via peer to peer network so block chain can be updated
- **"mining" confirms transactions by adding them to block chain**
  - competitive distributed consensus algorithm
  - takes work to confirm; new bitcoins created as a reward
  - blocks are protected by cryptographic hashing; each new one depends on previous ones

Crypto politics

- **cryptographic techniques as weapons of war?**
  - until recently, (strong) cryptography was classified as "munitions" in USA
  - falls under International Traffic in Arms Regulations and follow-ons
- **export control laws prohibited export of cryptographic code**
  - though it was ok to export books and T-shirts with code
    and everyone else in the world had it anyway
  - changed during 2000, but there are still restrictions
- **does the government have the right/duty ...**
  - to control cryptographic algorithms and programs?
  - to require trapdoors, key escrow, or similar mechanisms?
  - to prevent reverse-engineering of cryptographic devices?
  - to prevent research in cryptographic techniques?
- **do corporations have the right ...**
  - to prevent publication of cryptographic techniques?
  - to prevent reverse-engineering of cryptographic devices?
- **how do we balance individual rights, property rights, & societal rights?**

Summary of crypto

- **secret/symmetric key algorithms: DES, AES**
  - key distribution problem: everyone has to have the key
- **public key algorithms: RSA, ...**
  - solves key distribution problem, but authentication is still important
  - also permits digital signatures
  - much slower than secret key, so used mainly for key exchange
- **security is entirely in the key**
  - "security by obscurity" does not work: bad guys know everything
  - brute force attacks work if keys are too short or easy
- **good cryptography is hard**
  - you can't invent your own methods
  - you can't trust "secret" or proprietary methods
- **people are the weak link**
  - complicated or awkward systems will be subverted, ignored or misused
  - social engineering attacks are effective
    ignorance, incompetence, misguided helpfulness
- **if all else fails, try bribery, burglary, blackmail, brutality**

Cryptography is important

- **it protects our privacy and security**
  - access to computers
  - email
  - online shopping, banking, taxes
  - electronic voting
  - ...

- **it can restrict our rights and freedoms**
  - digital rights management: limits on what we can do with music, movies, software, ...

- **it helps good guys and bad guys alike**