CSE 484 / CSE M 584 (Winter 2013)

(Continue) Cryptography + (Back to) Software Security

Tadayoshi Kohno

Thanks to Vitaly Shmatikov, Dan Boneh, Dieter Gollmann, Dan Halperin, John Manferdelli, John Mitchell, Bennet Yee, and many others for sample slides and materials ...

Goals for Today

- Cryptography
- Software security (now that you’ve had more experience with Lab 1)

- HW2 out soon (on cryptography)

Note: Optimizing Exponentiation

- How to compute M^x mod N? Say x=13
- Sums of power of 2, $x = 8+4+1 = 2^3+2^2+2^0$
- Can also write x in binary, e.g., x = 1101
- Can solve by repeated squaring
  - $y = 1;$
  - $y = y^2 * M \bmod N$ // $y = M$
  - $y = y^2 * M \bmod N$ // $y = M^2 * M = M^{2+1} = M^3$
  - $y = y^2 \bmod N$ // $y = (M^{2+1})^2 = M^{4+2}$
  - $y = y^2 * M \bmod N$ // $y = (M^{4+2})^2 * M = M^{8+4+1}$
- Does anyone see a potential issue?

Timing attacks

Collect timings for exponentiation with a bunch of messages M1, M2, ... (e.g., RSA signing operations with a private exponent)

Assume (inductively) know b_3=1, b_2=1, guess b_1=1

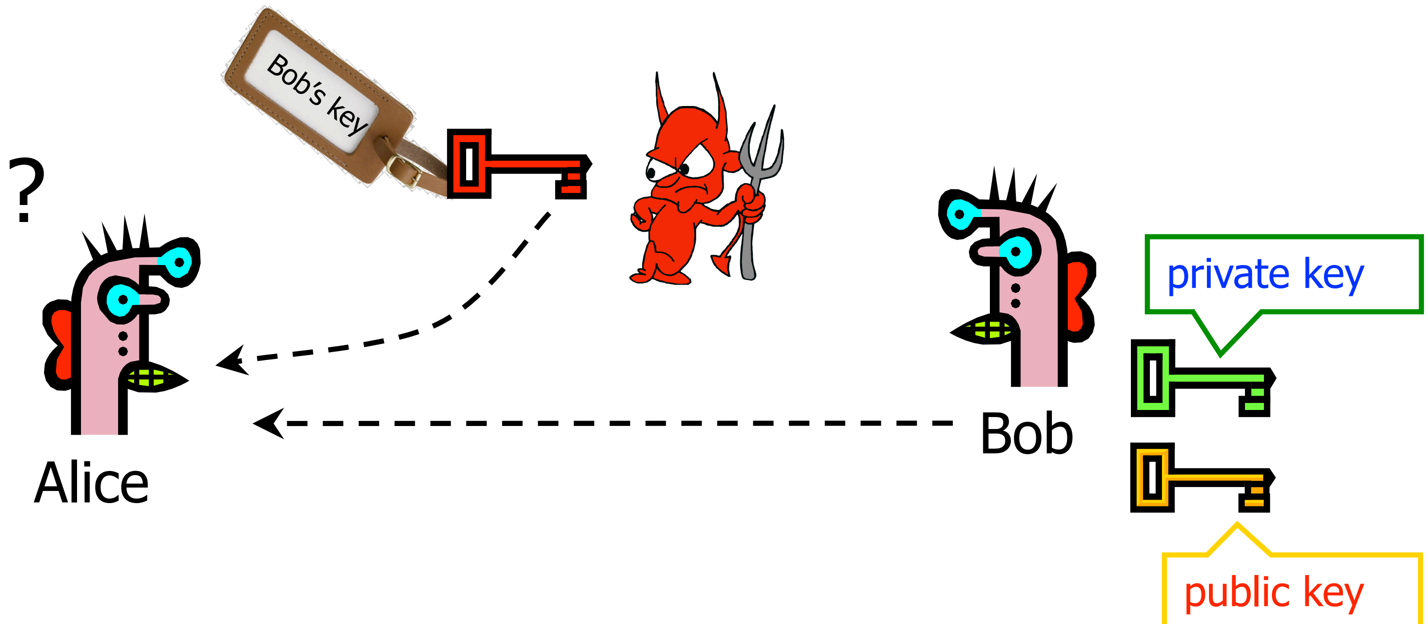
i	b_i = 0	b_i = 1	Comp	Meas
3	$y = y^2$ mod N	$y = y^2$ * M1 mod N		
2	$y = y^2$ mod N	$y = y^2$ * M1 mod N		
1	$y = y^2$ mod N	$y = y^2$ * M1 mod N	X1 secs	
0	$y = y^2$ mod N	$y = y^2$ * M1 mod N		Y1 secs

i	b_i = 0	b_i = 1	Comp	Meas
3	$y = y^2$ mod N	$y = y^2$ * M2 mod N		
2	$y = y^2$ mod N	$y = y^2$ * M2 mod N		
1	$y = y^2$ mod N	$y = y^2$ * M2 mod N	X2 secs	
0	$y = y^2$ mod N	$y = y^2$ * M2 mod N		Y2 secs

Timing attacks

- If $b_1 = 1$, then set of { Yj - Xj | j in {1,2, ..} } has distribution with "small" variance (due to time for final step, i=0)
  - "Guess" was correct when we computed X1, X2, ...
- If $b_1 = 0$, then set of { Yj - Xj | j in {1,2, ..} } has distribution with "large" variance (due to time for final step, i=0, and incorrect guess for b_1)
  - "Guess" was incorrect when we computed X1, X2, ...
  - So time computation wrong (Xj computed as large, but really small, ...)
- Strategy: Force user to sign large number of messages M1, M2, ... Record timings for signing.
- Iteratively learn bits of key by using above property.

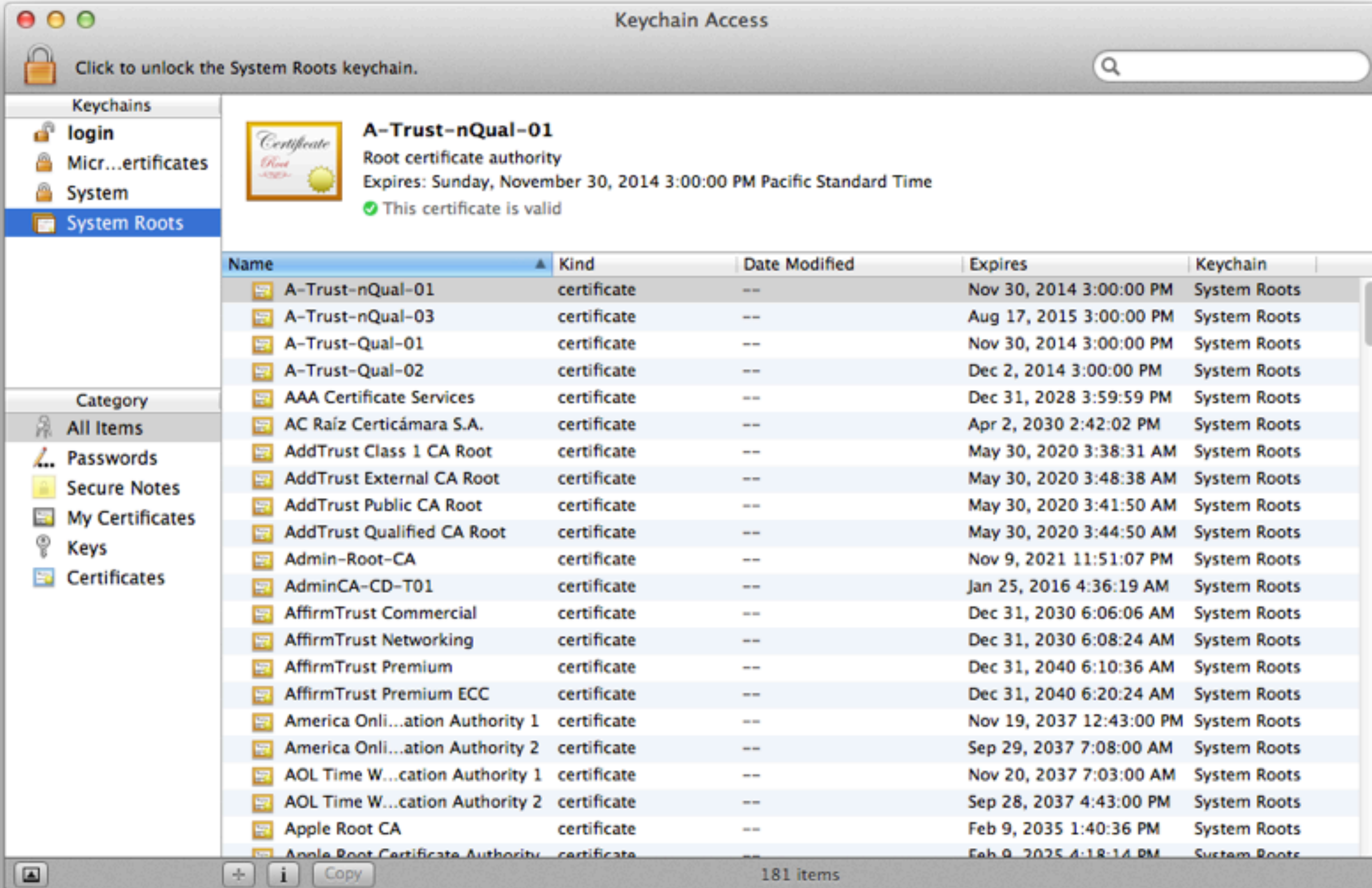
Authenticity of Public Keys



Problem: How does Alice know that the public key she received is really Bob's public key?

Distribution of Public Keys

- Public announcement or public directory
  - Risks: forgery and tampering
- Public-key certificate
  - Signed statement specifying the key and identity
    - sig_{CA}("Bob", PK_B)
- Common approach: certificate authority (CA)
  - Single agency responsible for certifying public keys
  - After generating a private/public key pair, user proves his identity and knowledge of the private key to obtain CA's certificate for the public key (offline)
  - Every computer is pre-configured with CA's public key


Keychain Access
Click to unlock the System Roots keychain.
Keychains
login
Micr...ertificates
System
System Roots
A-Trust-nQual-01
Root certificate authority
Expires: Sunday, November 30, 2014 3:00:00 PM Pacific Standard Time
This certificate is valid
Name
Kind
Date Modified
Expires
Keychain
A-Trust-nQual-01 certificate -- Nov 30, 2014 3:00:00 PM System Roots
A-Trust-nQual-03 certificate -- Aug 17, 2015 3:00:00 PM System Roots
A-Trust-Qual-01 certificate -- Nov 30, 2014 3:00:00 PM System Roots
A-Trust-Qual-02 certificate -- Dec 2, 2014 3:00:00 PM System Roots
AAA Certificate Services certificate -- Dec 31, 2028 3:59:59 PM System Roots
AC Raíz Certicámara S.A. certificate -- Apr 2, 2030 2:42:02 PM System Roots
AddTrust Class 1 CA Root certificate -- May 30, 2020 3:38:31 AM System Roots
AddTrust External CA Root certificate -- May 30, 2020 3:48:38 AM System Roots
AddTrust Public CA Root certificate -- May 30, 2020 3:41:50 AM System Roots
AddTrust Qualified CA Root certificate -- May 30, 2020 3:44:50 AM System Roots
Admin-Root-CA certificate -- Nov 9, 2021 11:51:07 PM System Roots
AdminCA-CD-T01 certificate -- Jan 25, 2016 4:36:19 AM System Roots
AffirmTrust Commercial certificate -- Dec 31, 2030 6:06:06 AM System Roots
AffirmTrust Networking certificate -- Dec 31, 2030 6:08:24 AM System Roots
AffirmTrust Premium certificate -- Dec 31, 2040 6:10:36 AM System Roots
AffirmTrust Premium ECC certificate -- Dec 31, 2040 6:20:24 AM System Roots
America Onli...ation Authority 1 certificate -- Nov 19, 2037 12:43:00 PM System Roots
America Onli...ation Authority 2 certificate -- Sep 29, 2037 7:08:00 AM System Roots
AOL Time W...cation Authority 1 certificate -- Nov 20, 2037 7:03:00 AM System Roots
AOL Time W...cation Authority 2 certificate -- Sep 28, 2037 4:43:00 PM System Roots
Apple Root CA certificate -- Feb 9, 2035 1:40:36 PM System Roots
Category
All Items
Passwords
Secure Notes
My Certificates
Keys
Certificates
Copy
181 items

Hierarchical Approach

- Single CA certifying every public key is impractical
- Instead, use a trusted root authority
  - For example, Verisign
  - Everybody must know the public key for verifying root authority's signatures
- Root authority signs certificates for lower-level authorities, lower-level authorities sign certificates for individual networks, and so on
  - Instead of a single certificate, use a certificate chain
    - $sig_{Verisign}$("AnotherCA", $PK_{AnotherCA}$), $sig_{AnotherCA}$("Alice", PK_A)
  - What happens if root authority is ever compromised?

Many Challenges

Spoofing URLs With Unicode

Posted by timothy **on Mon May 27, '02 09:48 PM**
from the **there-is-a-problem-with-this-certificate** dept.

Embedded Geek writes:

> "Scientific American has an interesting article about how a pair of students at the Technion-Israel Institute of Technology registered "microsoft.com" with Verisign, using the Russian Cyrillic letters "c" and "o". Even though it is a completely different domain, the two display identically (the article uses the term "homograph"). The work was done for a paper in the **Communications of the ACM** (the paper itself is not online). The article characterizes attacks using this spoof as "scary, if not entirely probable," assuming that a hacker would have to first take over a page at another site. I disagree: sending out a mail message with the URL waiting to be clicked ("Bill Gates will send you ten dollars!") is just one alternate technique. While security problems with Unicode have been noted here before, this might be a new twist."

http://it.slashdot.org/story/08/12/30/1655234/CCC-Create-a-Rogue-CA-Certificate
http://www.win.tue.nl/hashclash/rogue-ca/

Many Challenges

CCC Create a Rogue CA Certificate

Posted by CmdrTaco **on Tue Dec 30, 2008 12:14 PM**
from the **they-even-faked-this-dept** dept.

t3rmin4t0r writes

> "Just when you were breathing easy about Kaminsky, DNS and the word hijacking, by repeating the word SSL in your head, the hackers at CCC were busy at work making a hash of SSL certificate security. Here's the scoop on how they set up their own rogue CA, by (from what I can figure) reversing the hash and engineering a collision up in MD5 space. Until now, MD5 collisions have been ignored because nobody would put in that much effort to create a useful dummy file, but a CA certificate for phishing seems juicy enough to be fodder for the botnets now."

DigiNotar Hacked by Black.Spook and Iranian Hackers

Posted by Mikko @ 09:05 GMT | Comments

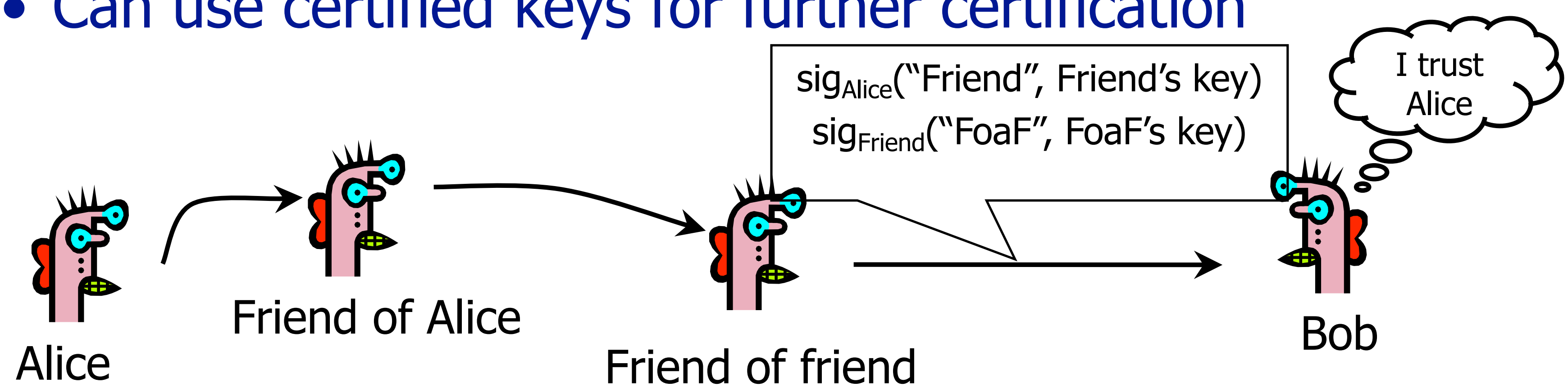
DigiNotar is a Dutch Certificate Authority. They sell SSL certificates.

Somehow, somebody managed to get a rogue SSL certificate from them on **July 10th, 2011**. This certificate was issued for domain name **.google.com**.

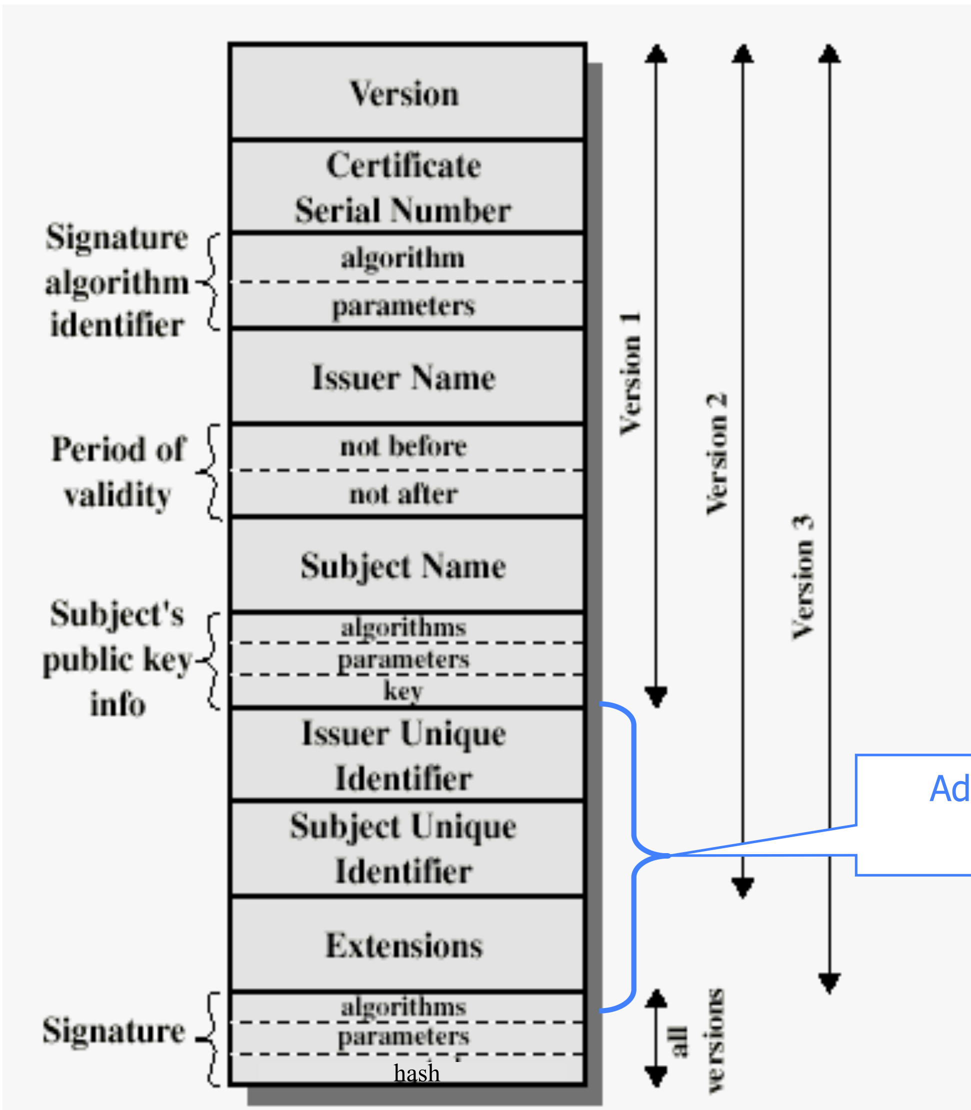
What can you do with such a certificate? Well, you can impersonate Google — assuming you can first reroute Internet traffic for google.com to you. This is something that can be done by a government or by a rogue ISP. Such a reroute would only affect users within that country or under that ISP.

Alternative: "Web of Trust"

- Used in PGP (Pretty Good Privacy)
- Instead of a single root certificate authority, each person has a set of keys they "trust"
  - If public-key certificate is signed by one of the "trusted" keys, the public key contained in it will be deemed valid
- Trust can be transitive
  - Can use certified keys for further certification



X.509 Certificate



Added in X.509 versions 2 and 3 to address usability and security problems

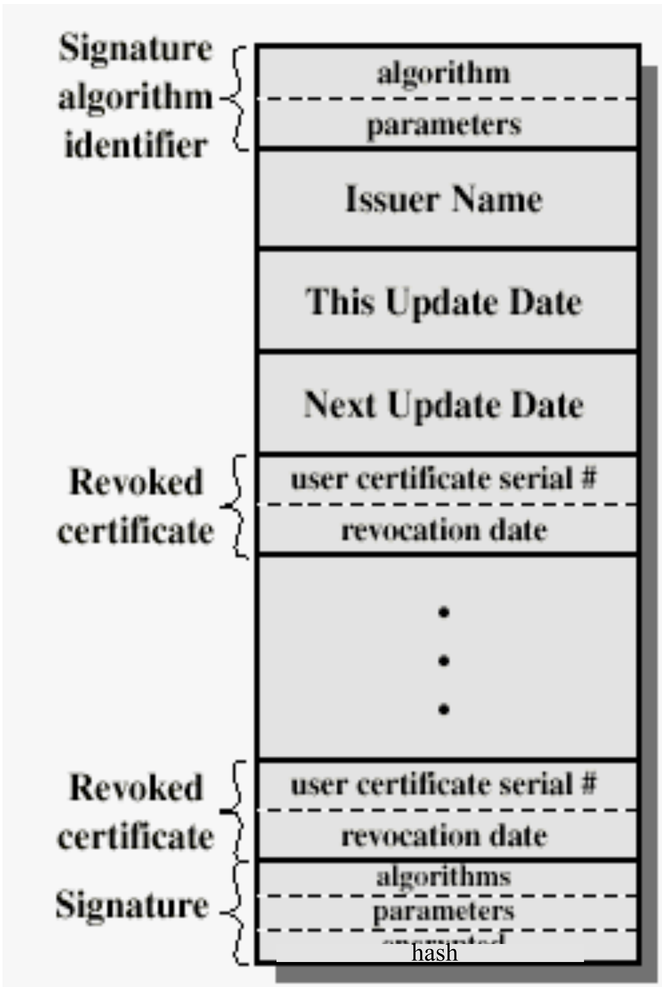
Certificate Revocation

- Revocation is <u>very</u> important
- Many valid reasons to revoke a certificate
  - Private key corresponding to the certified public key has been compromised
  - User stopped paying his certification fee to this CA and CA no longer wishes to certify him
  - CA's private key has been compromised!
- Expiration is a form of revocation, too
  - Many deployed systems don't bother with revocation
  - Re-issuance of certificates is a big revenue source for certificate authorities

Certificate Revocation Mechanisms

- Online revocation service
  - When a certificate is presented, recipient goes to a special online service to verify whether it is still valid
    - Like a merchant dialing up the credit card processor
- Certificate revocation list (CRL)
  - CA periodically issues a signed list of revoked certificates
    - Credit card companies used to issue thick books of canceled credit card numbers
  - Can issue a "delta CRL" containing only updates

X.509 Certificate Revocation List



Because certificate serial numbers must be unique within each CA, this is enough to identify the certificate

Convergence

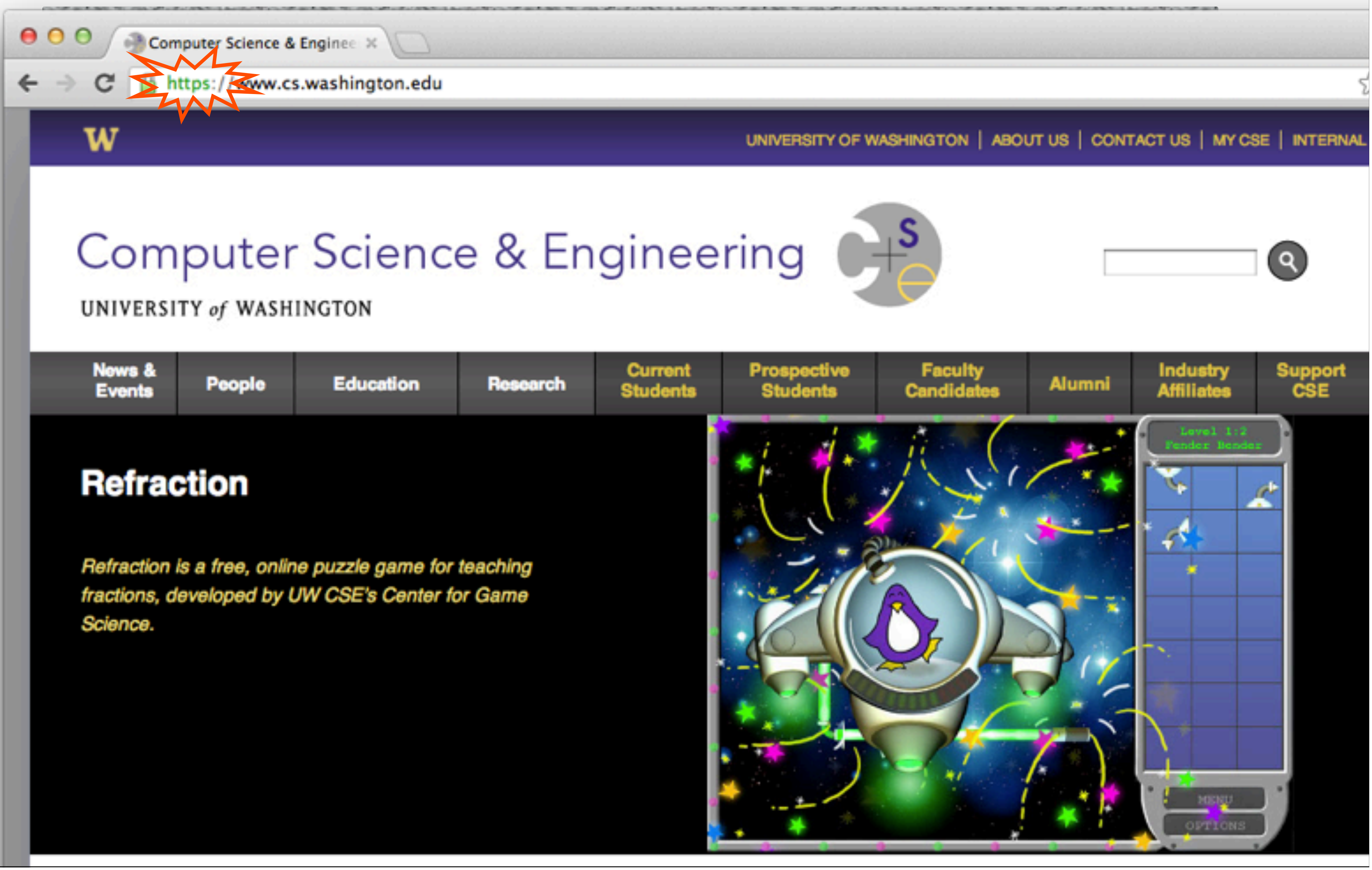
- Background observation:
  - MITM attacker will have a hard time mounting man-in-the-middle attacks against **all** clients around the world
- Basic idea:
  - Lots of nodes around the world obtaining SSL/TLS certificates from servers
  - Check responses across servers, and also observe unexpected changes from existing certificates

SSL

What is SSL / TLS?

- Transport Layer Security (TLS) protocol, version 1.2
  - De facto standard for Internet security
  - "The primary goal of the TLS protocol is to provide privacy and data integrity between two communicating applications"
  - In practice, used to protect information transmitted between browsers and Web servers (and mail readers and ...)
- Based on Secure Sockets Layers (SSL) protocol, version 3.0
  - Same protocol design, different algorithms
- Deployed in nearly every Web browser

SSL / TLS in the Real World



History of the Protocol

- SSL 1.0
  - Internal Netscape design, early 1994?
  - Lost in the mists of time
- SSL 2.0
  - Published by Netscape, November 1994
  - Several weaknesses
- SSL 3.0
  - Designed by Netscape and Paul Kocher, November 1996
- TLS 1.0
  - Internet standard based on SSL 3.0, January 1999
  - Not interoperable with SSL 3.0
    - TLS uses HMAC instead of earlier MAC; can run on any port
- TLS 1.2
  - Remove dependencies to MD5 and SHA1

“Request for Comments”

- Network protocols are usually disseminated in the form of an RFC
- TLS version 1.0 is described in RFC 5246
- Intended to be a self-contained definition of the protocol
  - Describes the protocol in sufficient detail for readers who will be implementing it and those who will be doing protocol analysis
  - Mixture of informal prose and pseudo-code

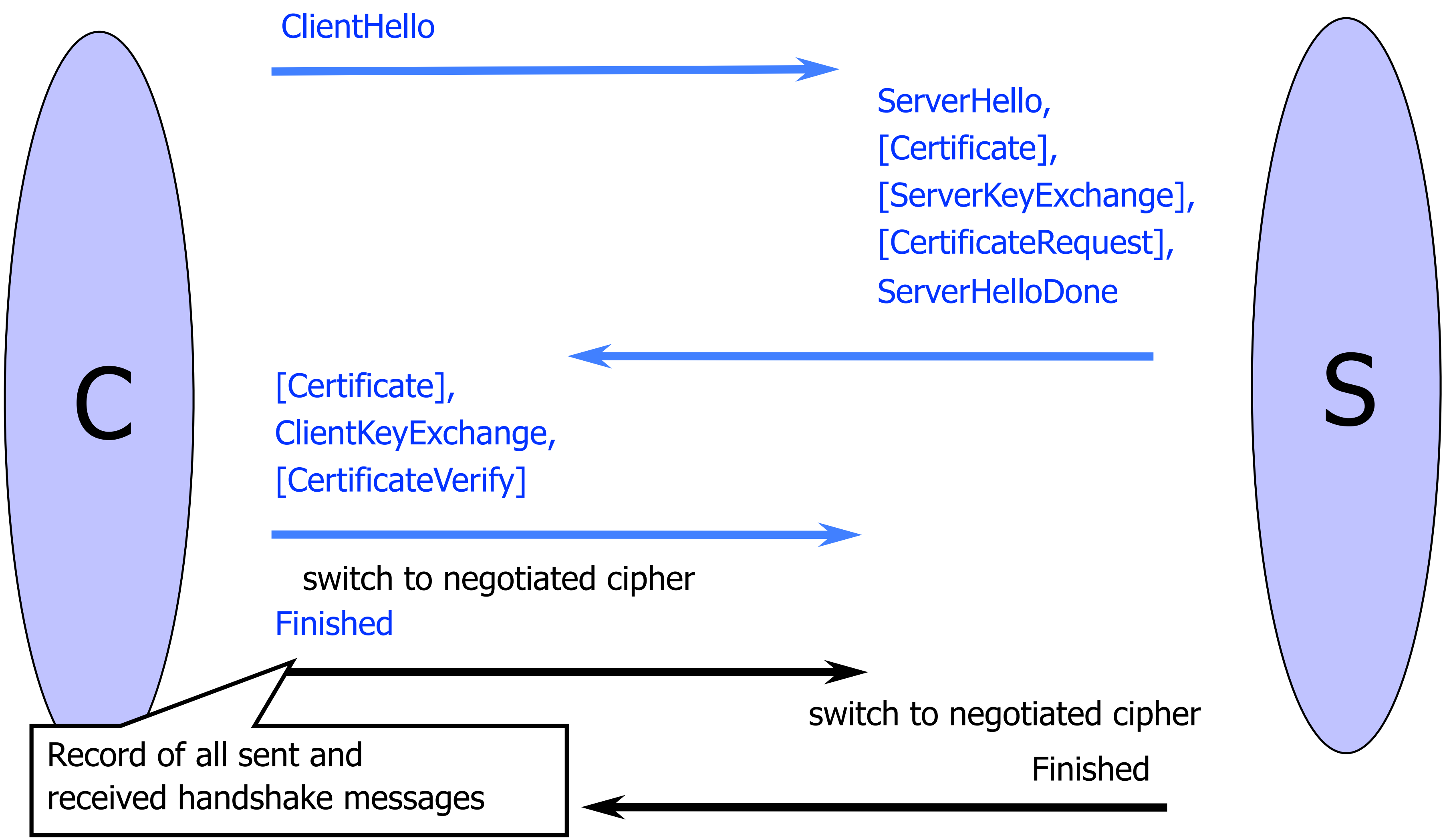
TLS Basics

- TLS consists of two protocols
  - Familiar pattern for key exchange protocols
- Handshake protocol
  - Use public-key cryptography to establish a shared secret key between the client and the server
- Record protocol
  - Use the secret key established in the handshake protocol to protect communication between the client and the server
- We will focus on the handshake protocol

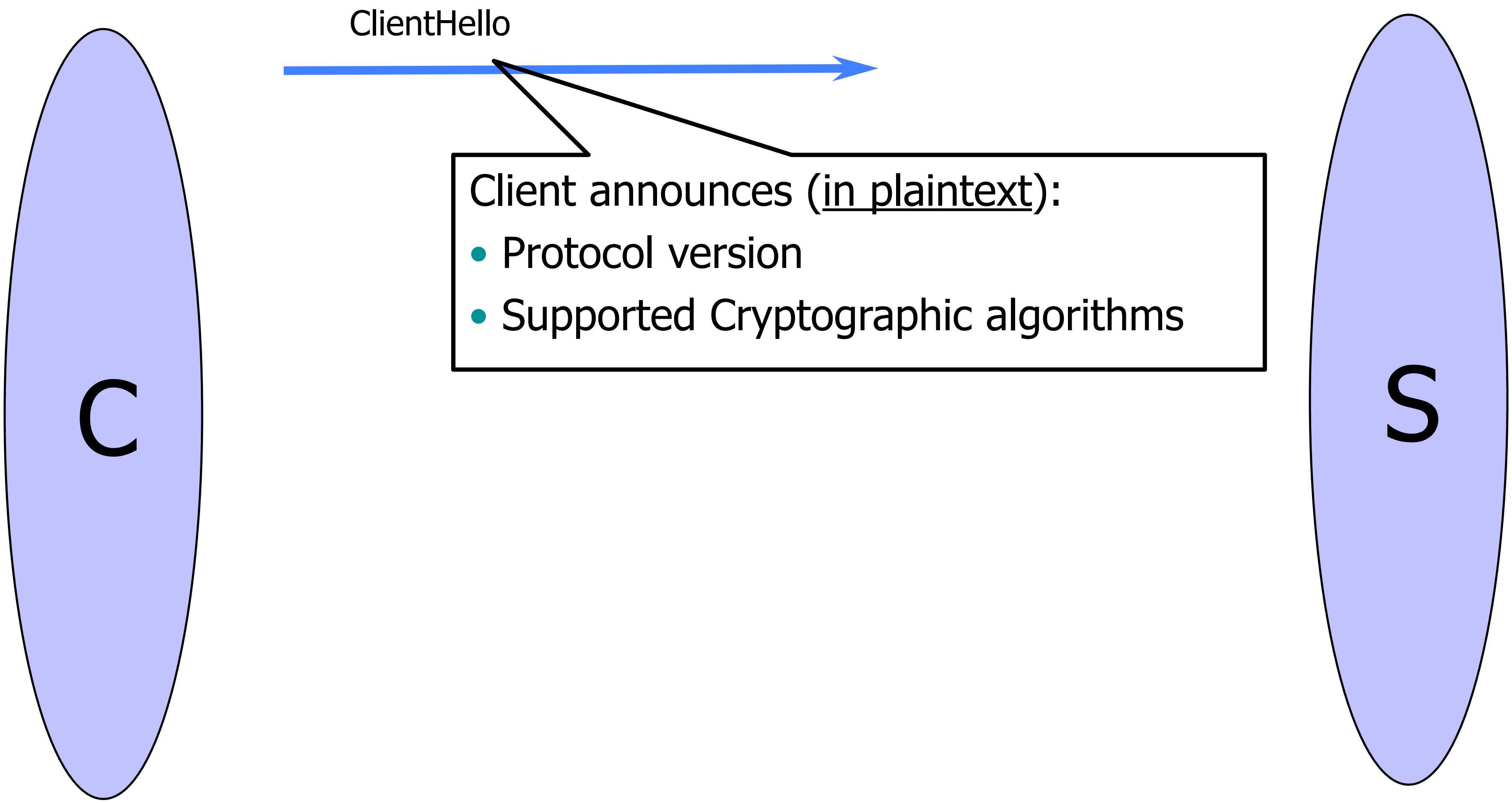
TLS Handshake Protocol

- Two parties: client and server
- Negotiate version of the protocol and the set of cryptographic algorithms to be used
  - Interoperability between different implementations of the protocol
- Authenticate client and server (optional)
  - Use digital certificates to learn each other's public keys and verify each other's identity
- Use public keys to establish a shared secret

Handshake Protocol Structure



ClientHello



Client announces (in plaintext):

- Protocol version
- Supported Cryptographic algorithms

ClientHello (RFC)

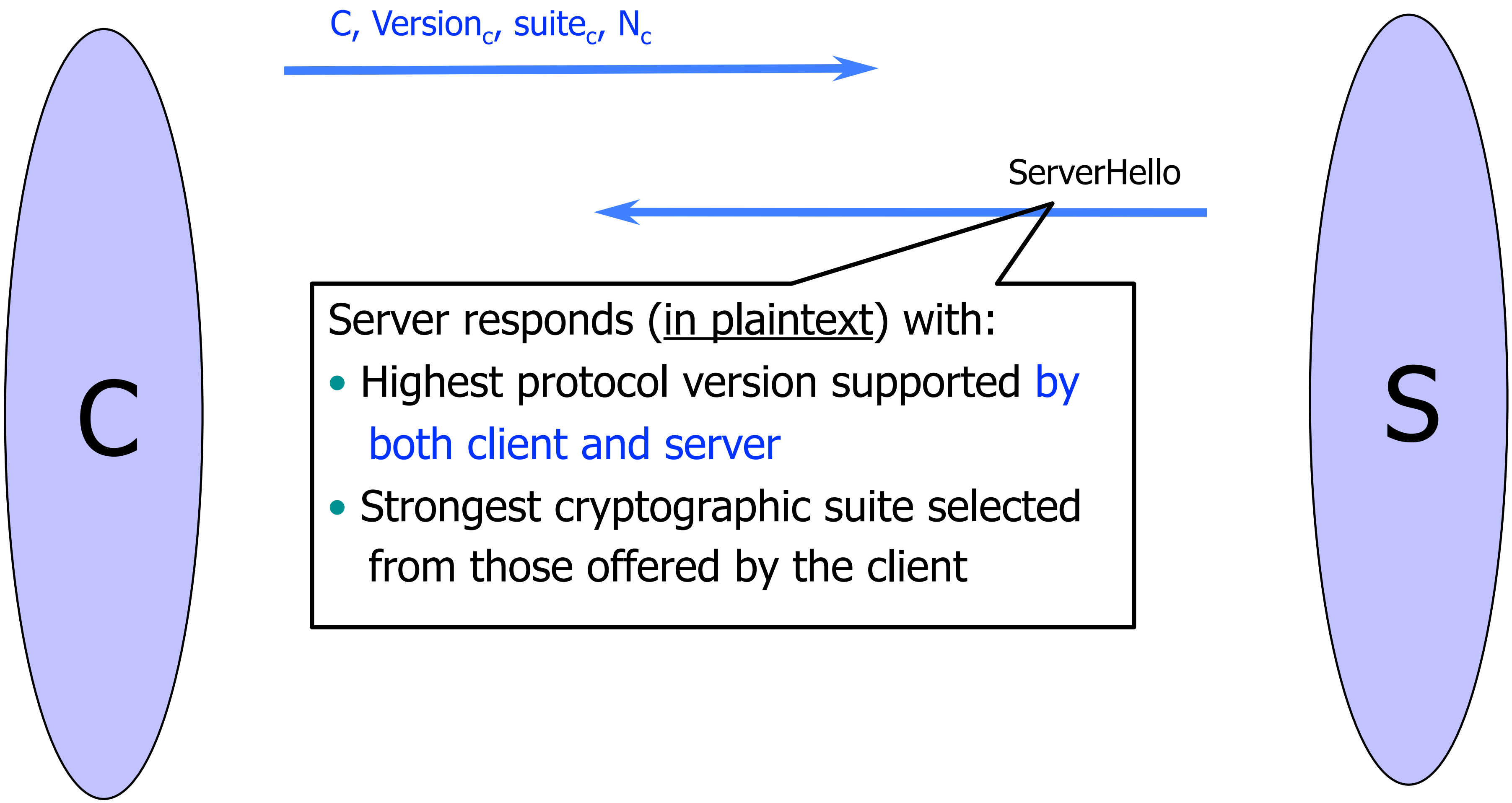
```
struct {
    ProtocolVersion client_version;
    Random random;
    SessionID session_id;
    CipherSuite cipher_suites;
    CompressionMethod compression_methods;
} ClientHello
```

Highest version of the protocol supported by the client

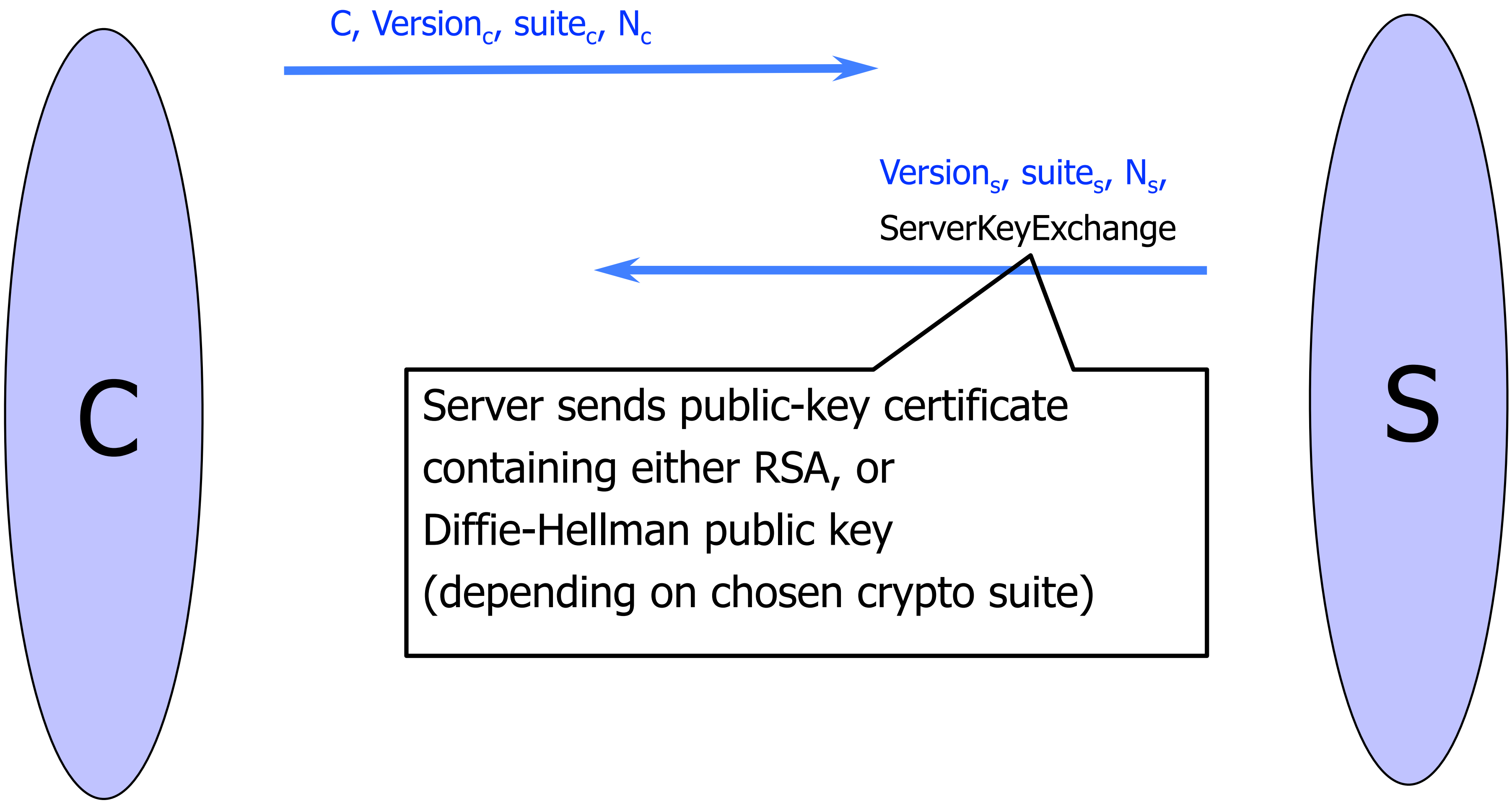
Session id (if the client wants to resume an old session)

Set of cryptographic algorithms supported by the client (e.g., RSA or Diffie-Hellman)

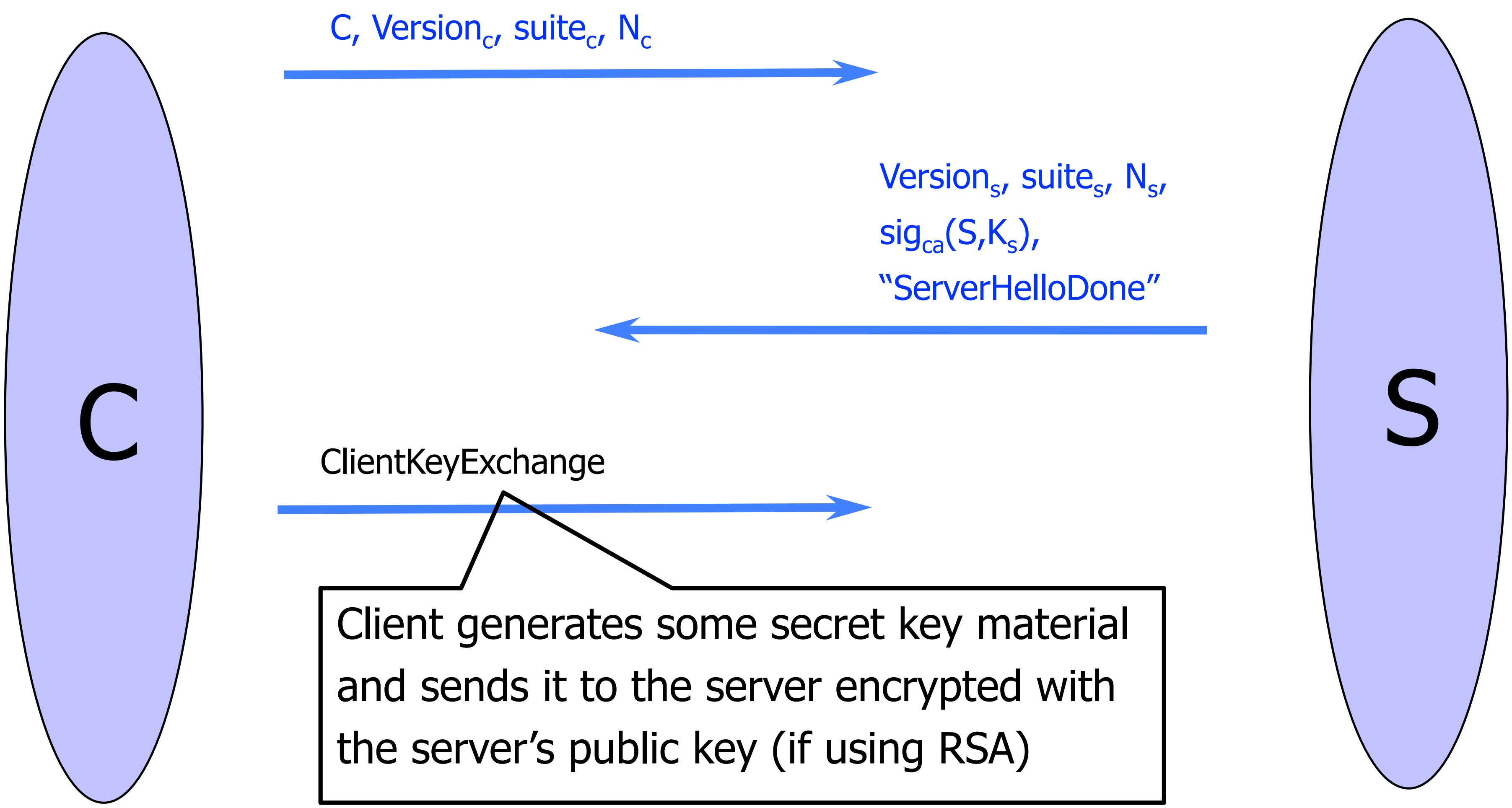
ServerHello



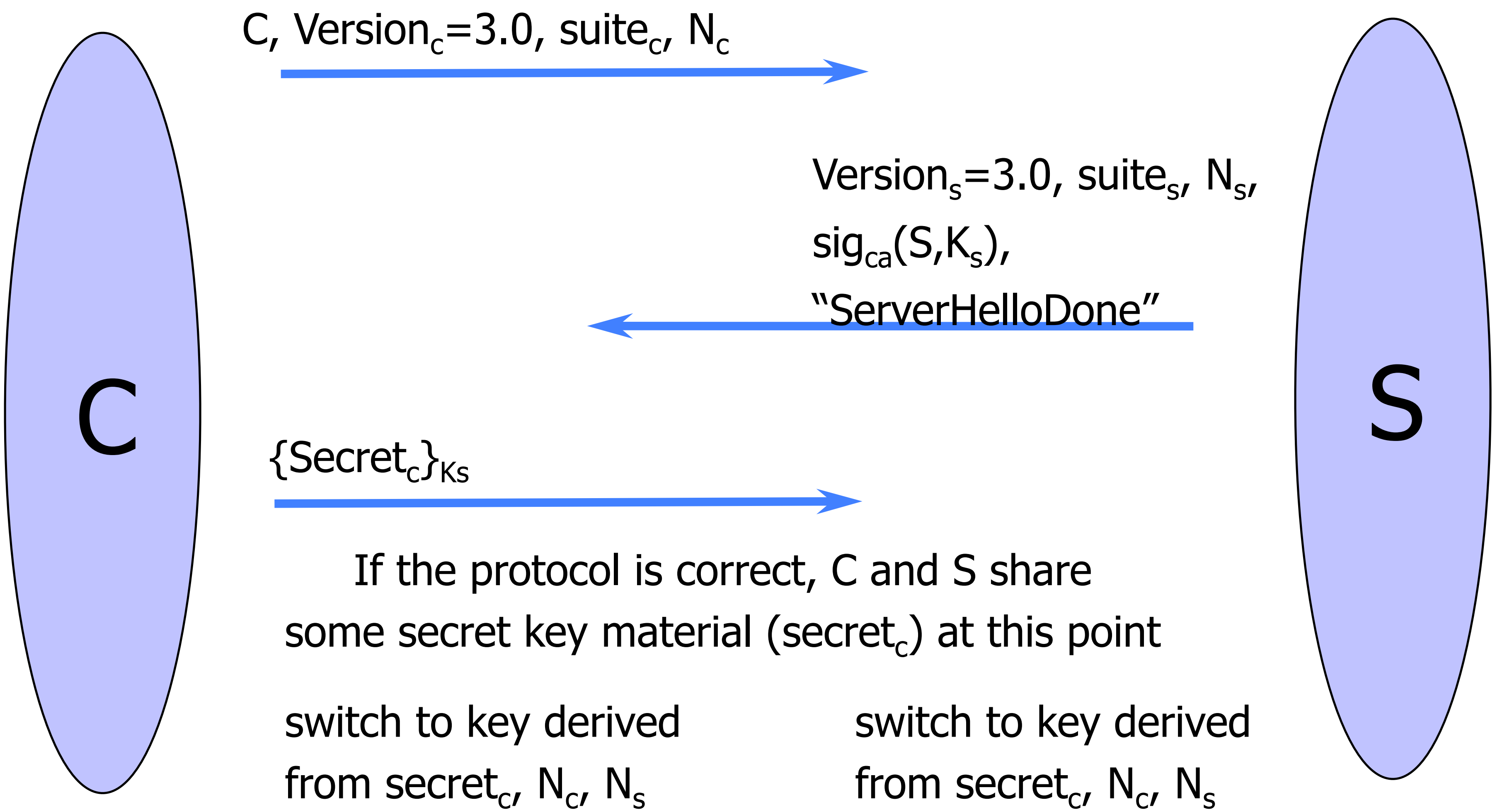
ServerKeyExchange



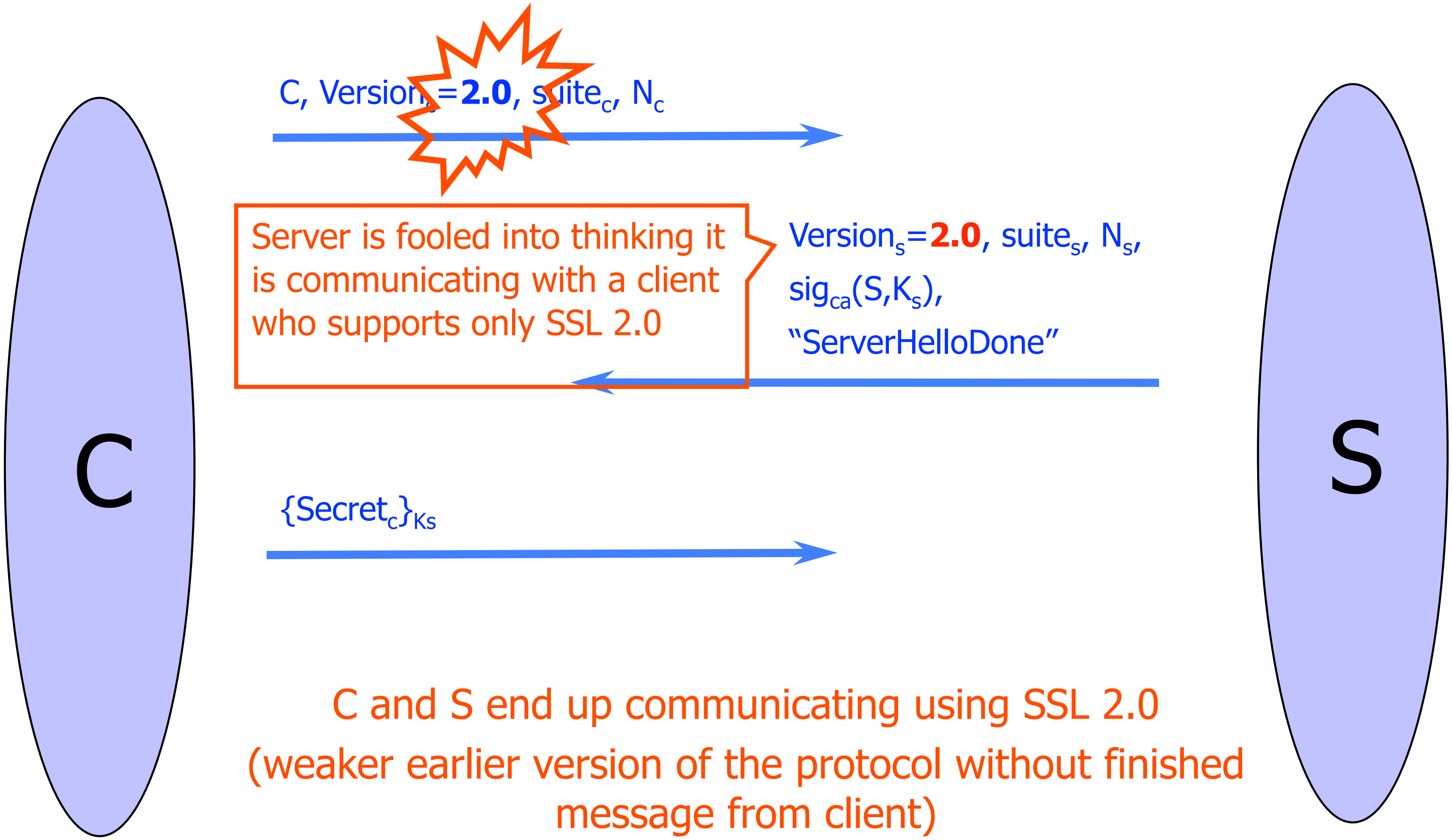
ClientKeyExchange



"Core" SSL 3.0 Handshake (Not TLS)



Version Rollback Attack



C and S end up communicating using SSL 2.0

(weaker earlier version of the protocol without finished message from client)

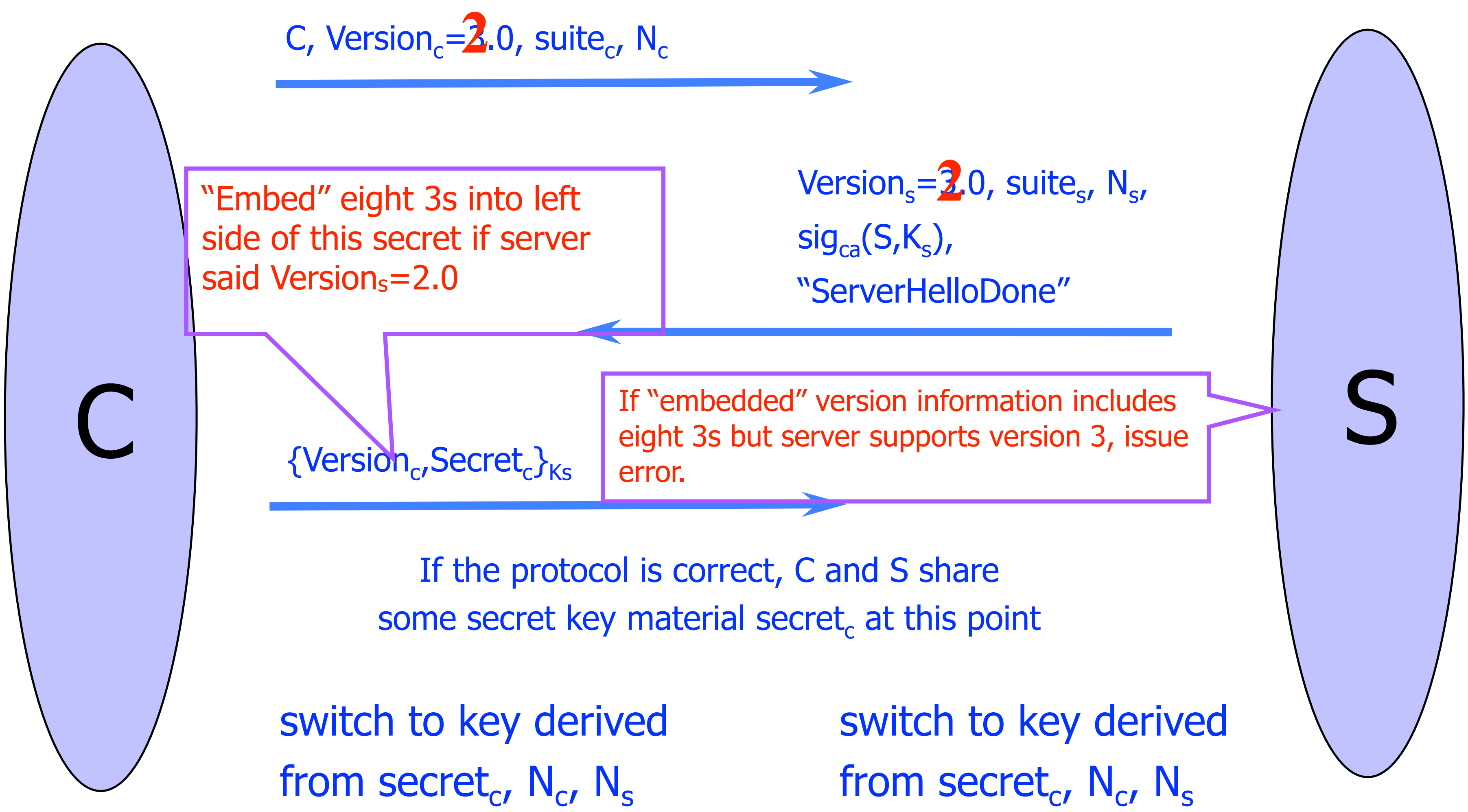
SSL 2.0 Weaknesses (Fixed in 3.0)

- Cipher suite preferences are not authenticated
  - "Cipher suite rollback" attack is possible
- SSL 2.0 uses padding when computing MAC in block cipher modes, but padding length field is not authenticated
  - Attacker can delete bytes from the end of messages
- MAC hash uses only 40 bits in export mode
- No support for certificate chains or non-RSA algorithms, no handshake while session is open

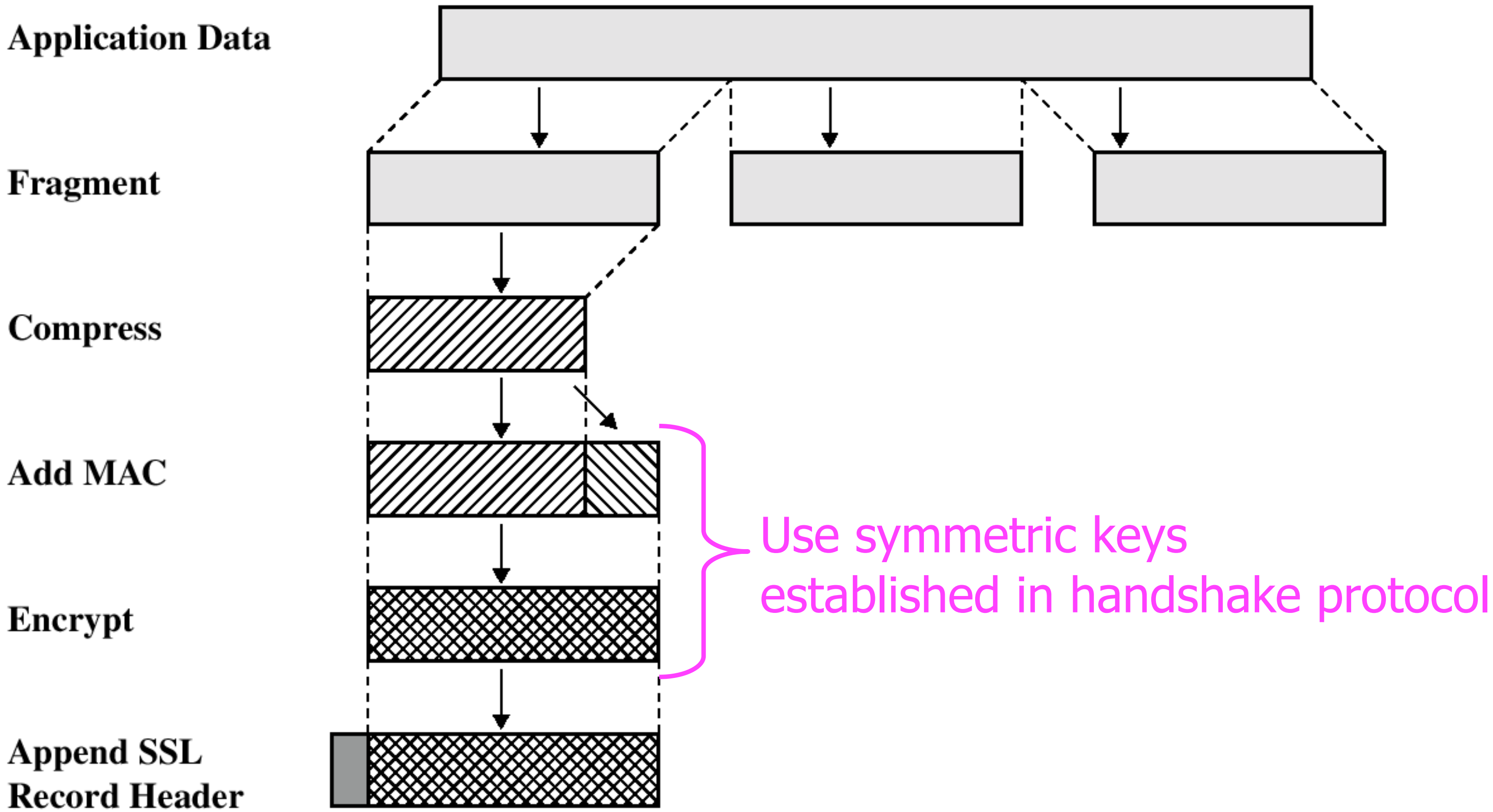
Protocol Rollback Attacks

- Why do people release new versions of security protocols? Because the old version got broken!
- New version must be backward-compatible
  - Not everybody upgrades right away
- Attacker can fool someone into using the old, broken version and exploit known vulnerability
  - Similar: fool victim into using weak crypto algorithms
- Defense is hard: must authenticate version in early designs
- Many protocols had "version rollback" attacks
  - SSL, SSH, GSM (cell phones)

Version Check in SSL 3.0 (Approximate)



SSL/TLS Record Protection



Summary

- Symmetric Crypto
  - Encryption
  - MACs
  - Dedicated Authenticated Encryption Schemes
    - GCM (Galois Counter Mode)
    - CCM
    - OCB
- Asymmetric Crypto
  - DH
  - RSA (encryption and signatures)
  - Authenticity of public keys
- Protocol rollback attacks

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Back to Software Security

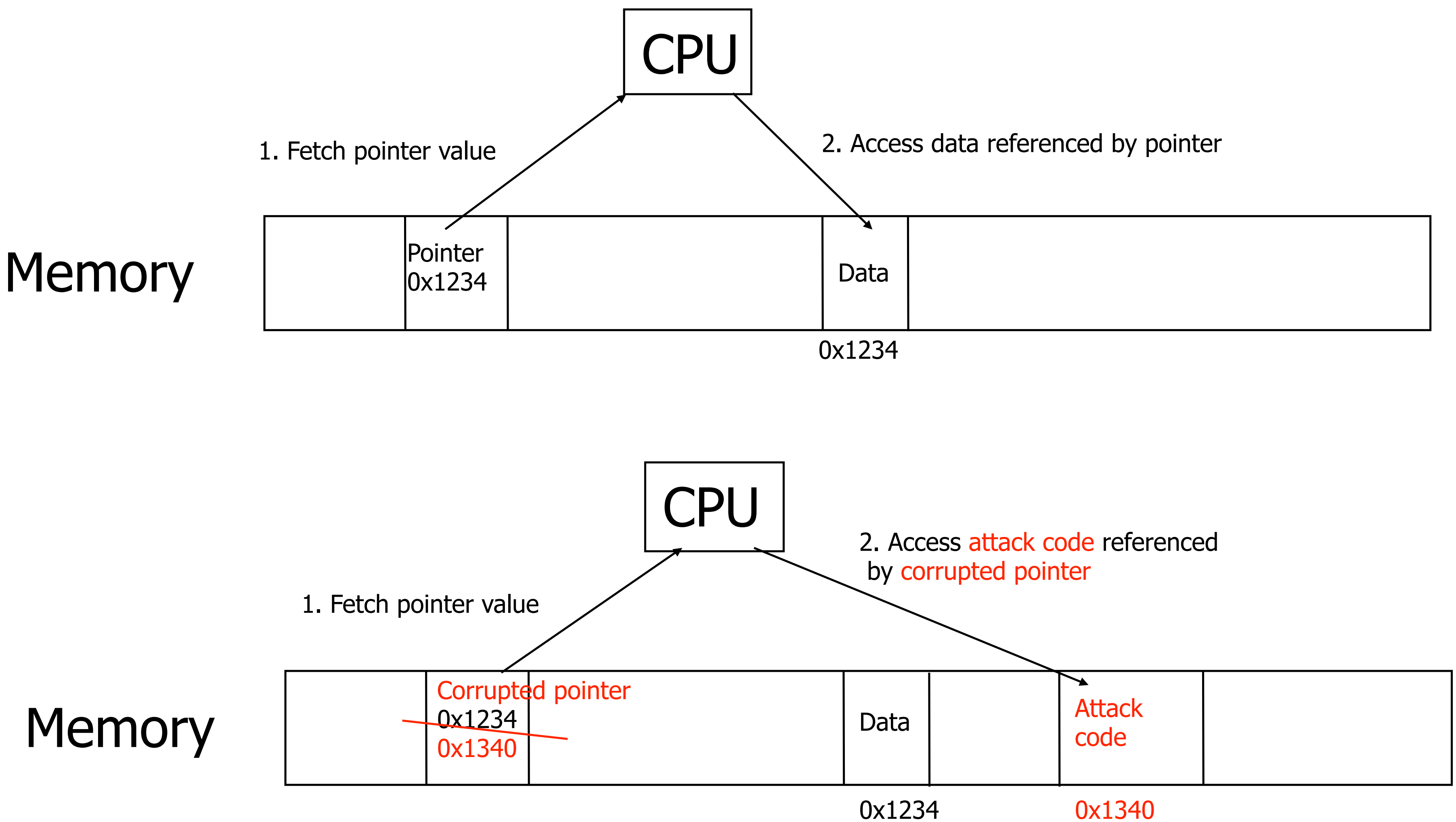
Defenses

- Already discussed Stack Guard: put canary on stack

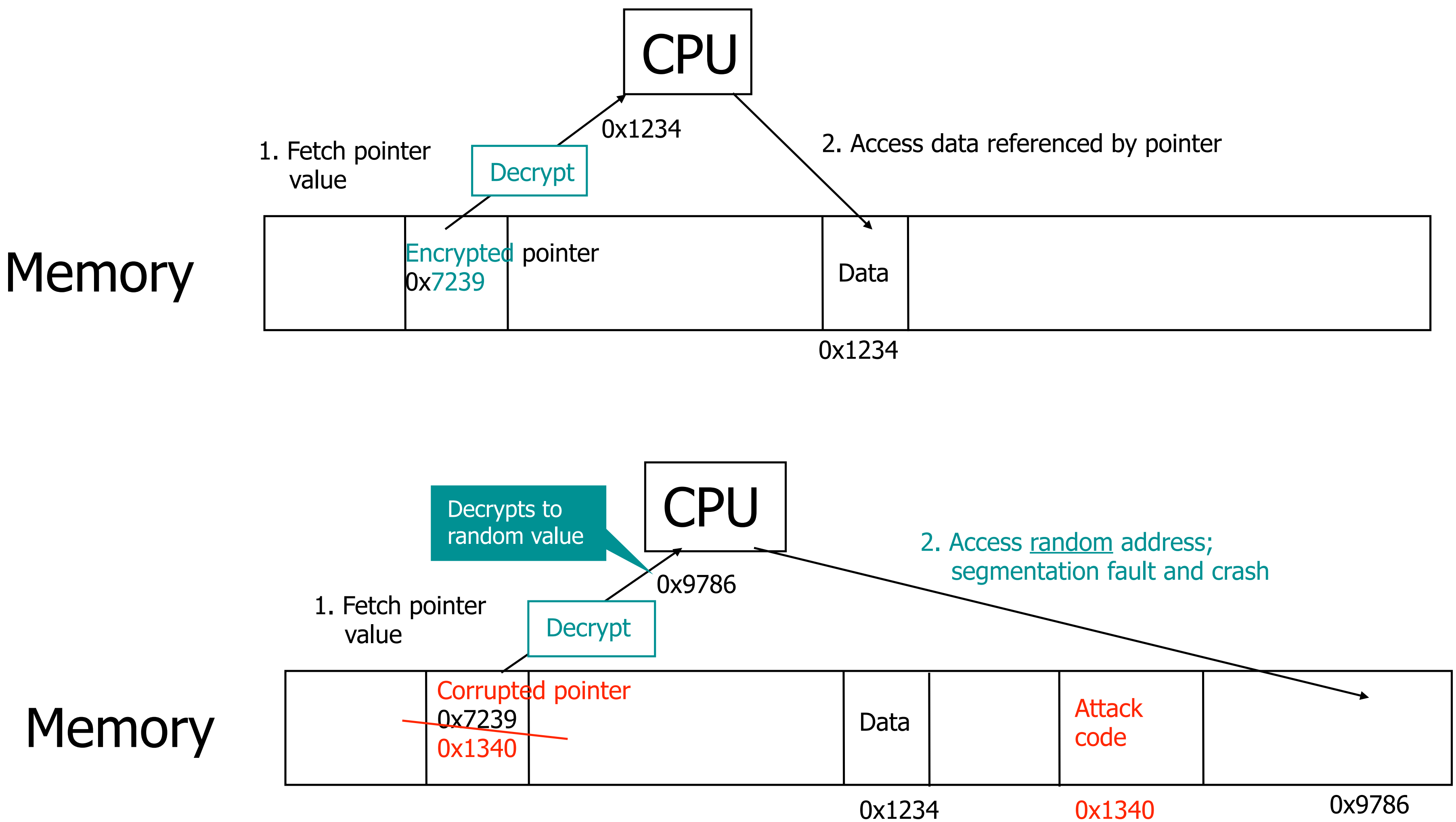
PointGuard

- Attack: overflow a function pointer so that it points to attack code
- Idea: encrypt all pointers while in memory
  - Generate a random key when program is executed
  - Each pointer is XORed with this key when loaded from memory to registers or stored back into memory
    - Pointers cannot be overflown while in registers
- Attacker cannot predict the target program's key
  - Even if pointer is overwritten, after XORing with key it will dereference to a "random" memory address

Normal Pointer Dereference [Cowan]



PointGuard Dereference [Cowan]



PointGuard Issues

- Must be very fast
  - Pointer dereferences are very common
- Compiler issues
  - Must encrypt and decrypt only pointers
  - If compiler "spills" registers, unencrypted pointer values end up in memory and can be overwritten there
- Attacker should not be able to modify the key
  - Store key in its own non-writable memory page
- PG'd code doesn't mix well with normal code
  - What if PG'd code needs to pass a pointer to OS kernel?

Other solutions to some of these issues

- Use safe programming languages, e.g., Java
  - What about legacy C code?
  - (Note that Java is not the complete solution)
- Program analysis of source code to find overflows
  - Coverity
  - Fortify
- Randomize stack location or encrypt return address on stack by XORing with random string
  - Attacker won’t know what address to use in his or her string

Fuzz Testing

- Generate "random" inputs to program
  - Sometimes conforming to input structures (file formats, etc)
- See if program crashes
  - If crashes, found a bug
  - Bug may be exploitable
- Surprisingly effective
- Now standard part of development lifecycle

Next slides special thanks to Hovav Shacham and Vitaly Shmatikov

Buffer Overflow: Causes and Cures

- Typical memory exploit involves code injection
  - Put malicious code in a predictable location in memory, usually masquerading as data
  - Trick vulnerable program into passing control to it
    - Overwrite saved EIP, function callback pointer, etc.
- Defense: prevent execution of untrusted code
  - Make stack and other data areas non-executable
    - Note: messes up useful functionality (e.g., ActionScript)
  - Digitally sign all code
  - Ensure that all control transfers are into a trusted, approved code image

W$\oplus$X / DEP

- Mark all writeable memory locations as non-executable
  - Example: Microsoft's DEP - Data Execution Prevention
  - This blocks many (not all) code injection exploits
- Hardware support
  - AMD "NX" bit, Intel "XD" bit (in post-2004 CPUs)
  - OS can make a memory page non-executable
- Widely deployed
  - Windows (since XP SP2), Linux (via PaX patches), OpenBSD, OS X (since 10.5)

What Does W⊕X Not Prevent?

- Can still corrupt stack …
  - … or function pointers or critical data on the heap
- As long as "saved EIP" points into existing code, W⊕X protection will not block control transfer
- This is the basis of return-to-libc exploits
  - Overwrite saved EIP with address of any library routine, arrange memory to look like arguments
- May not look like a huge threat
  - Attacker cannot execute arbitrary code
  - … especially if system() is not available

return-to-libc on Steroids (Hovav Shacham, CCS 2007)

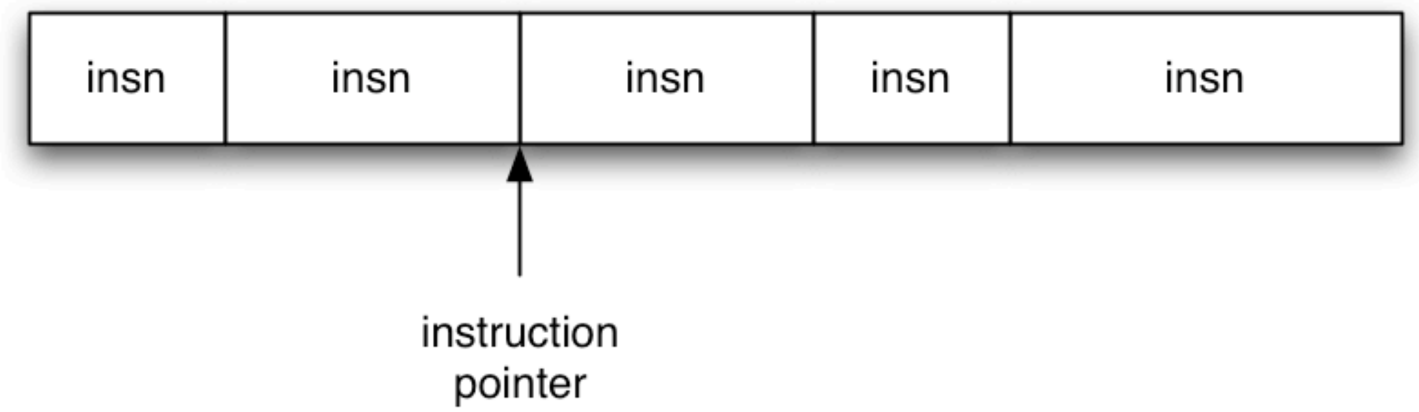
- Overwritten saved EIP need not point to the beginning of a library routine
- **Any** existing instruction in the code image is fine
  - Will execute the sequence starting from this instruction
- What if instruction sequence contains RET?
  - Execution will be transferred… to where?
  - Read the word pointed to by stack pointer (ESP)
    - Guess what? Its value is under attacker's control! (why?)
  - Use it as the new value for EIP
    - Now control is transferred to an address of attacker's choice!
  - Increment ESP to point to the next word on the stack

Chaining RETs for Fun and Profit

[Shacham et al]

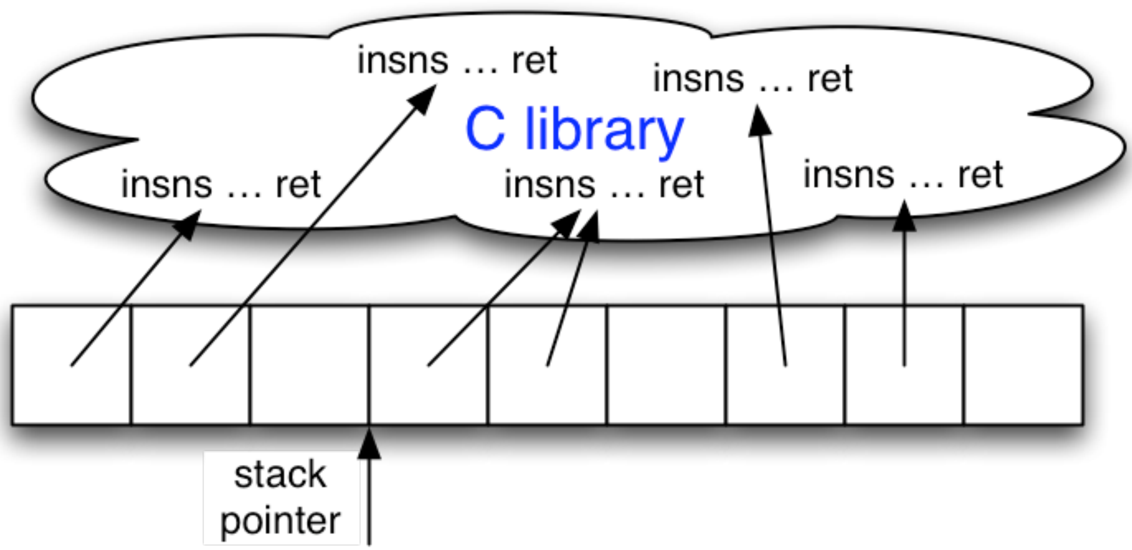
- Can chain together sequences ending in RET
  - Krahmer, "x86-64 buffer overflow exploits and the borrowed code chunks exploitation technique" (2005)
- What is this good for?
- Answer [Shacham et al.]: everything
  - Turing-complete language
  - Build "gadgets" for load-store, arithmetic, logic, control flow, system calls
  - **Attack can perform arbitrary computation using no injected code at all!**

Ordinary Programming



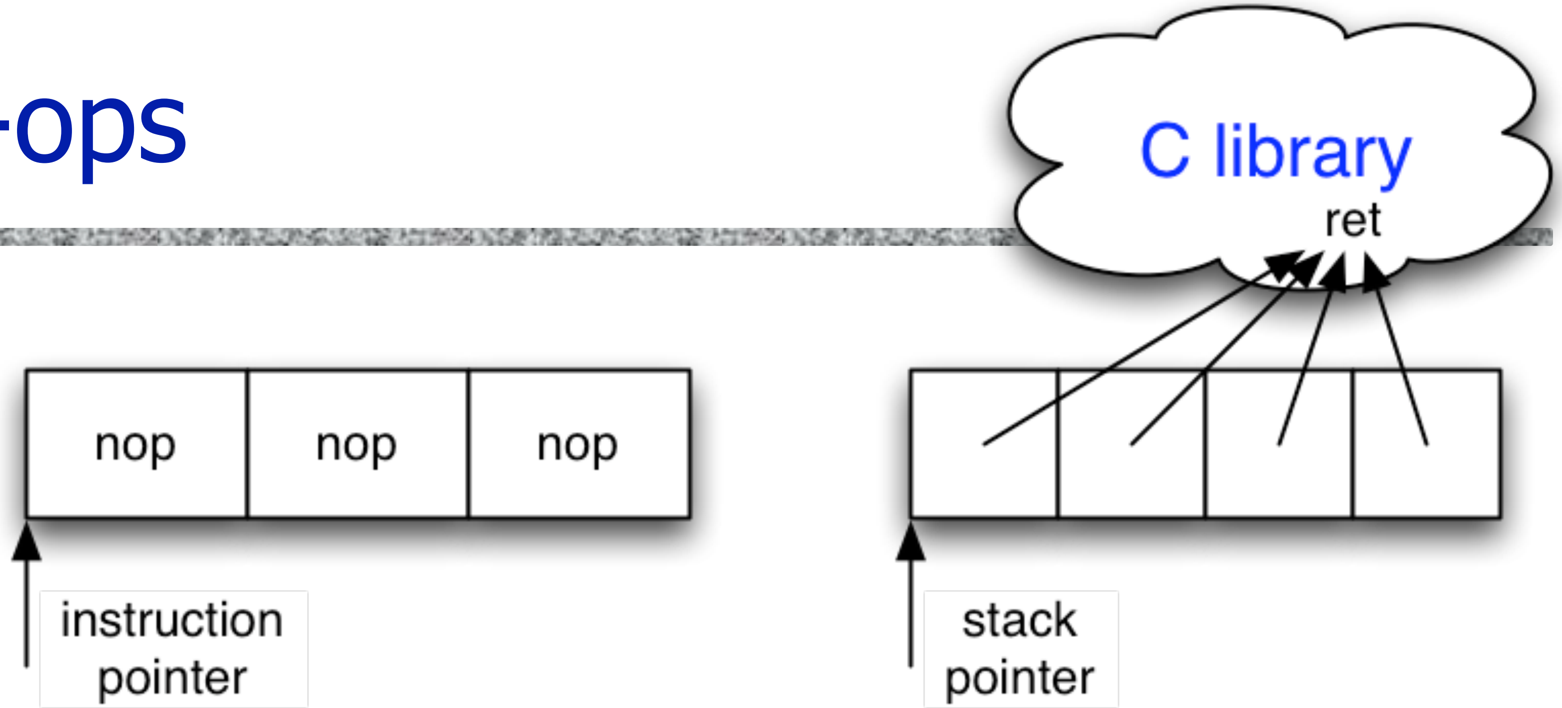
- Instruction pointer (EIP) determines which instruction to fetch and execute
- Once processor has executed the instruction, it automatically increments EIP to next instruction
- Control flow by changing value of EIP

Return-Oriented Programming



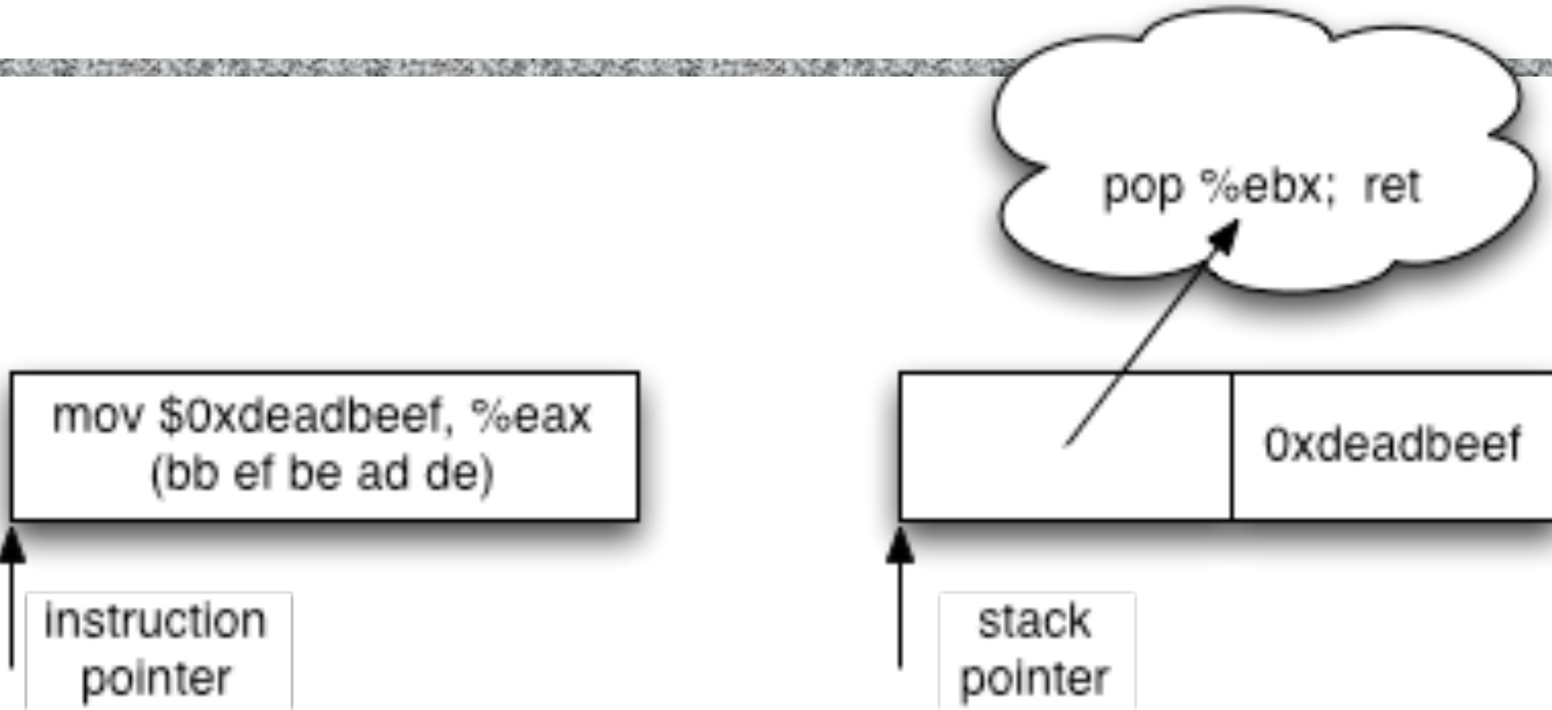
- **Stack pointer** (ESP) determines which instruction sequence to fetch and execute
- Processor doesn't automatically increment ESP
  - But the RET at end of each instruction sequence does

No-ops



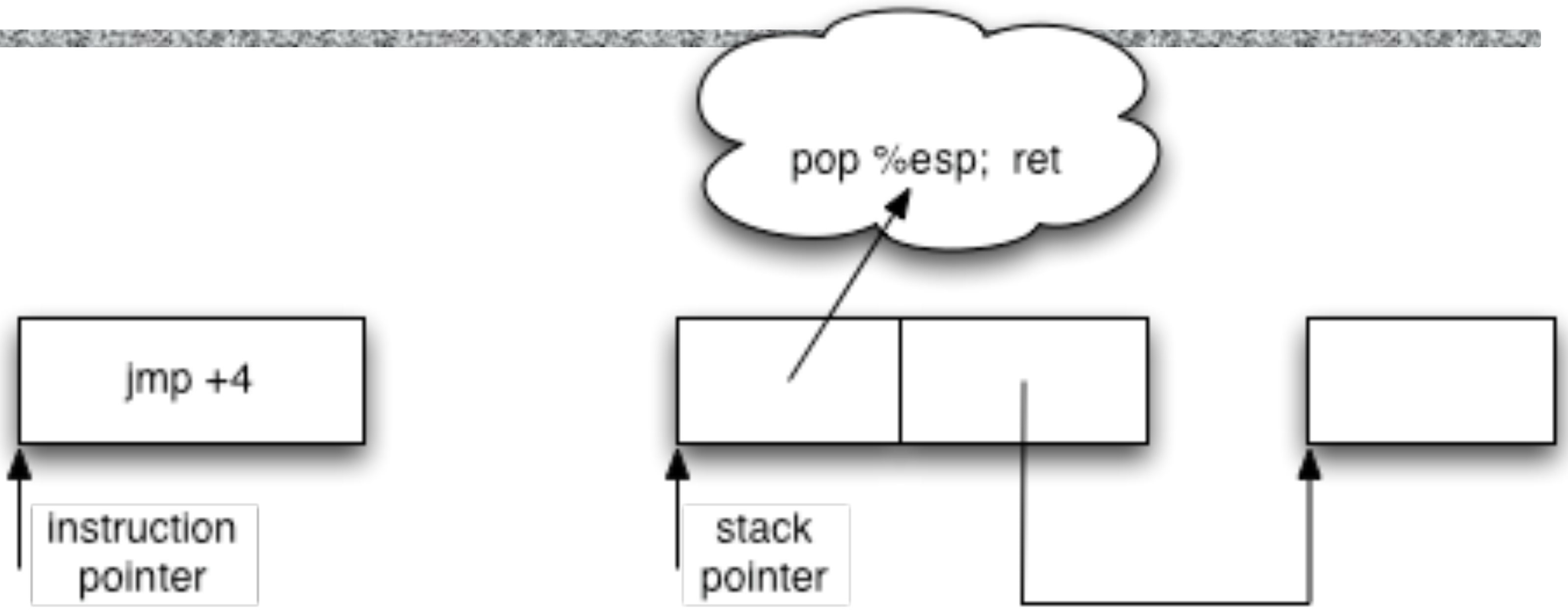
- No-op instruction does nothing but advance EIP
- Return-oriented equivalent
  - Point to return instruction
  - Advances ESP
- Useful -- like a NOP sled

Immediate Constants



- Instructions can encode constants
- Return-oriented equivalent
  - Store on the stack
  - Pop into register to use

Control Flow



- Ordinary programming
  - (Conditionally) set EIP to new value
- Return-oriented equivalent
  - (Conditionally) set ESP to new value