CS 395T

SSL / TLS Case Study

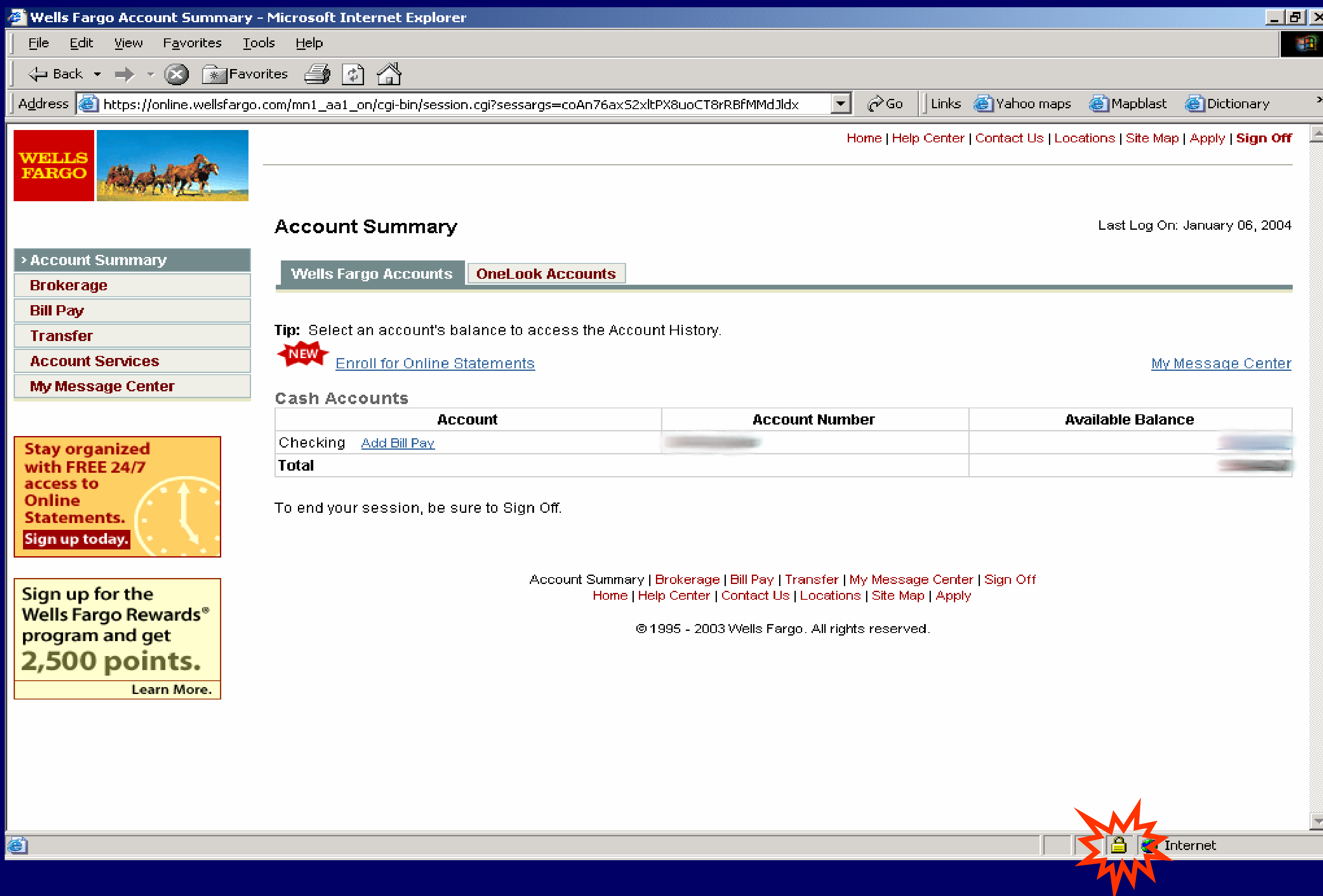
Overview

- Introduction to the SSL / TLS protocol
  - Widely deployed, “real-world” security protocol
- Protocol analysis case study
  - Start with the RFC describing the protocol
  - Create an abstract model and code it up in Murφ
  - Specify security properties
  - Run Murφ to check whether security properties are satisfied
- This lecture is a compressed version of what you will be doing in your project!

What is SSL / TLS?

- Transport Layer Security protocol, version 1.0
  - 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
- Based on Secure Sockets Layers protocol, ver 3.0
  - Same protocol design, different algorithms
- Deployed in nearly every Web browser

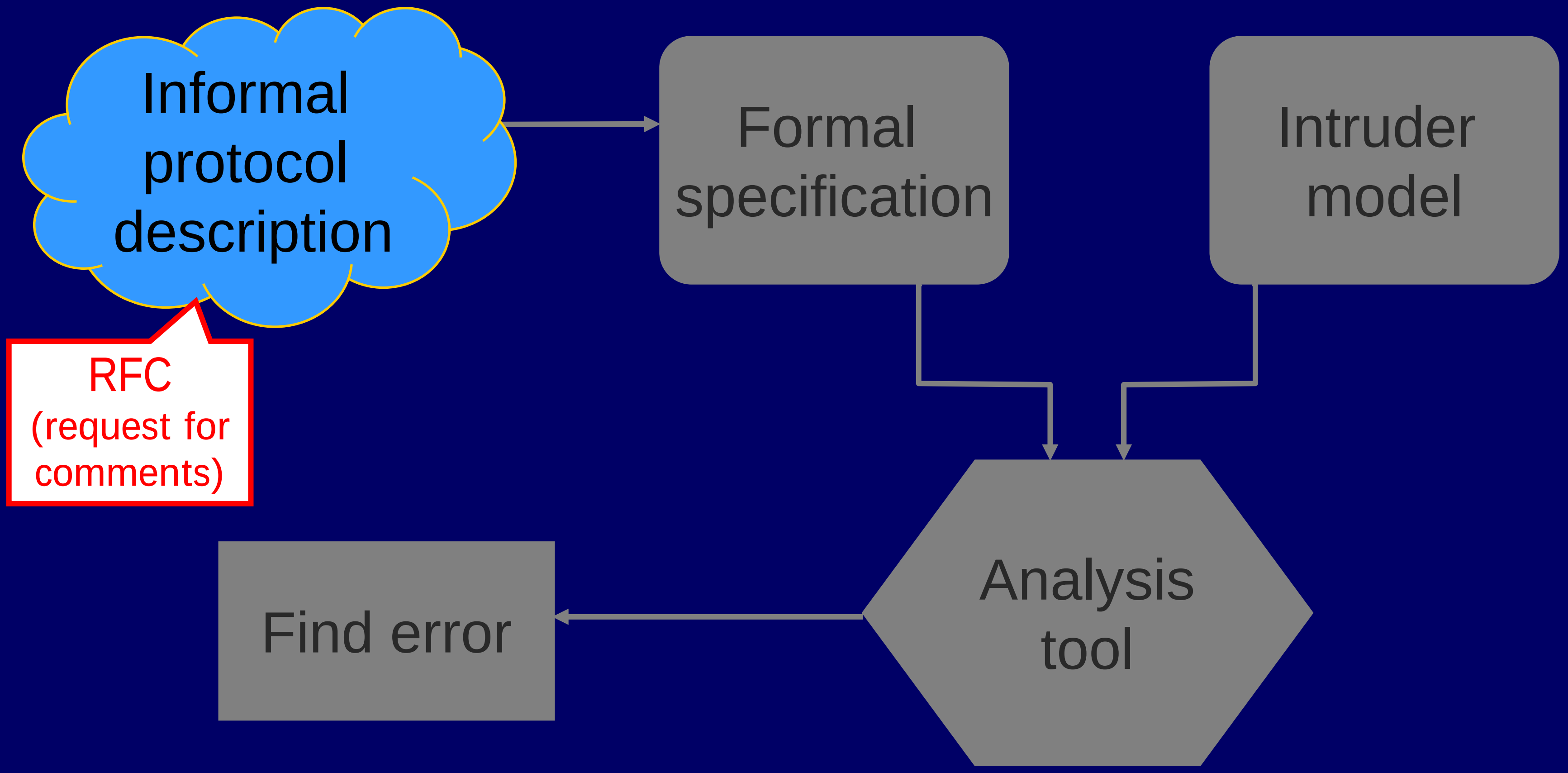
SSL / TLS in the Real World



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 MAC; can run on any port...

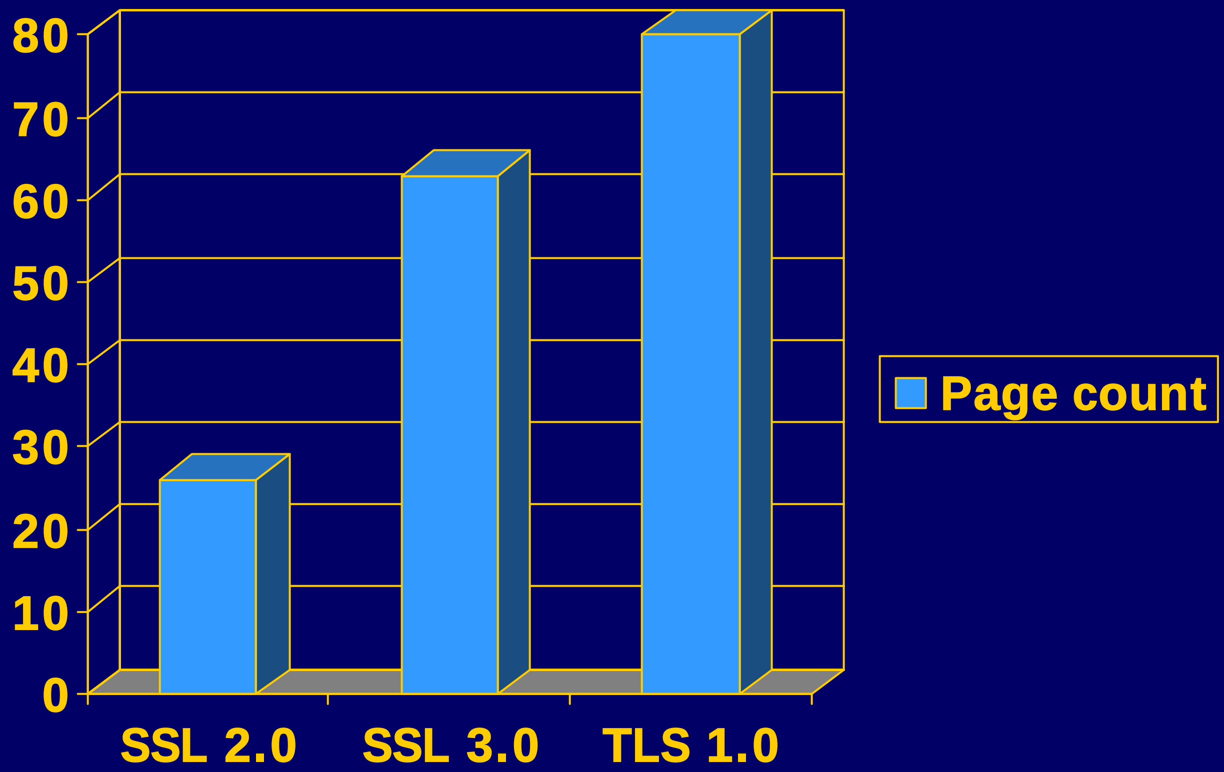
Let’s Get Going...



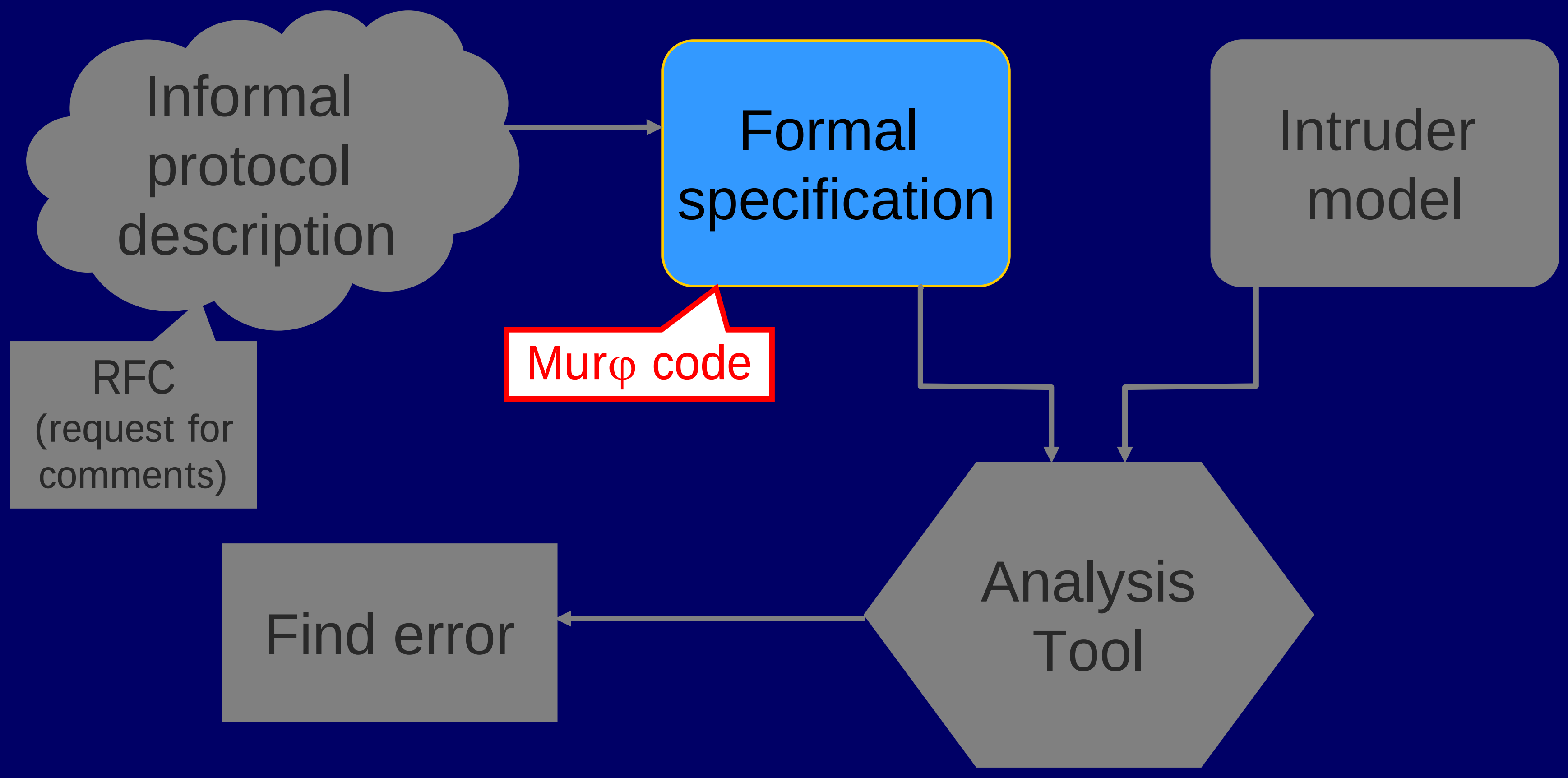
Request for Comments

- Network protocols are usually disseminated in the form of an RFC
- TLS version 1.0 is described in RFC 2246
- 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 (that’s <u>you</u>!)
  - Mixture of informal prose and pseudo-code
- Read some RFCs to get a flavor of what protocols look like when they emerge from the committee

Evolution of the SSL/TLS RFC



From RFC to Murφ Model



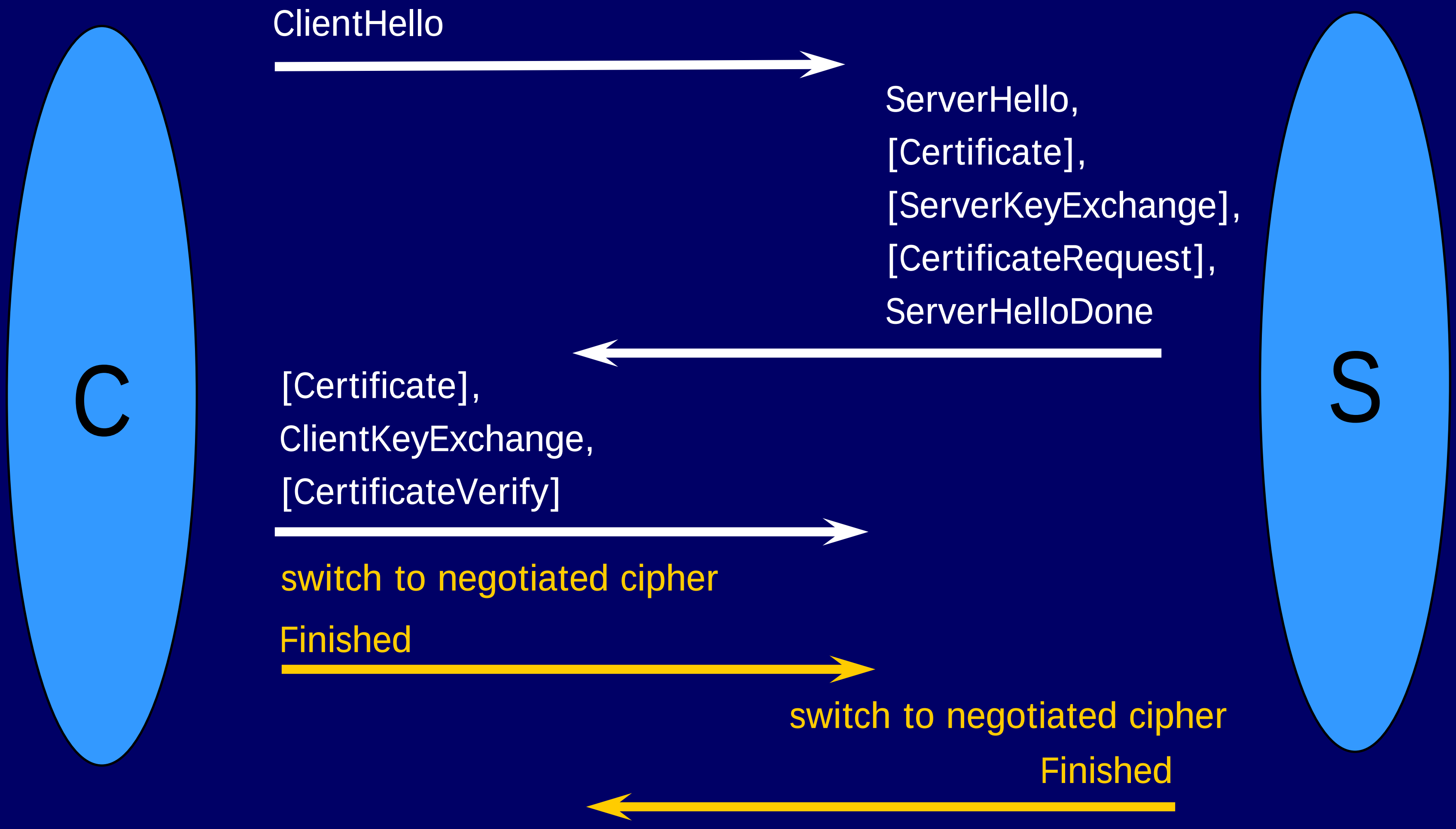
TLS Basics

- TLS consists of two 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



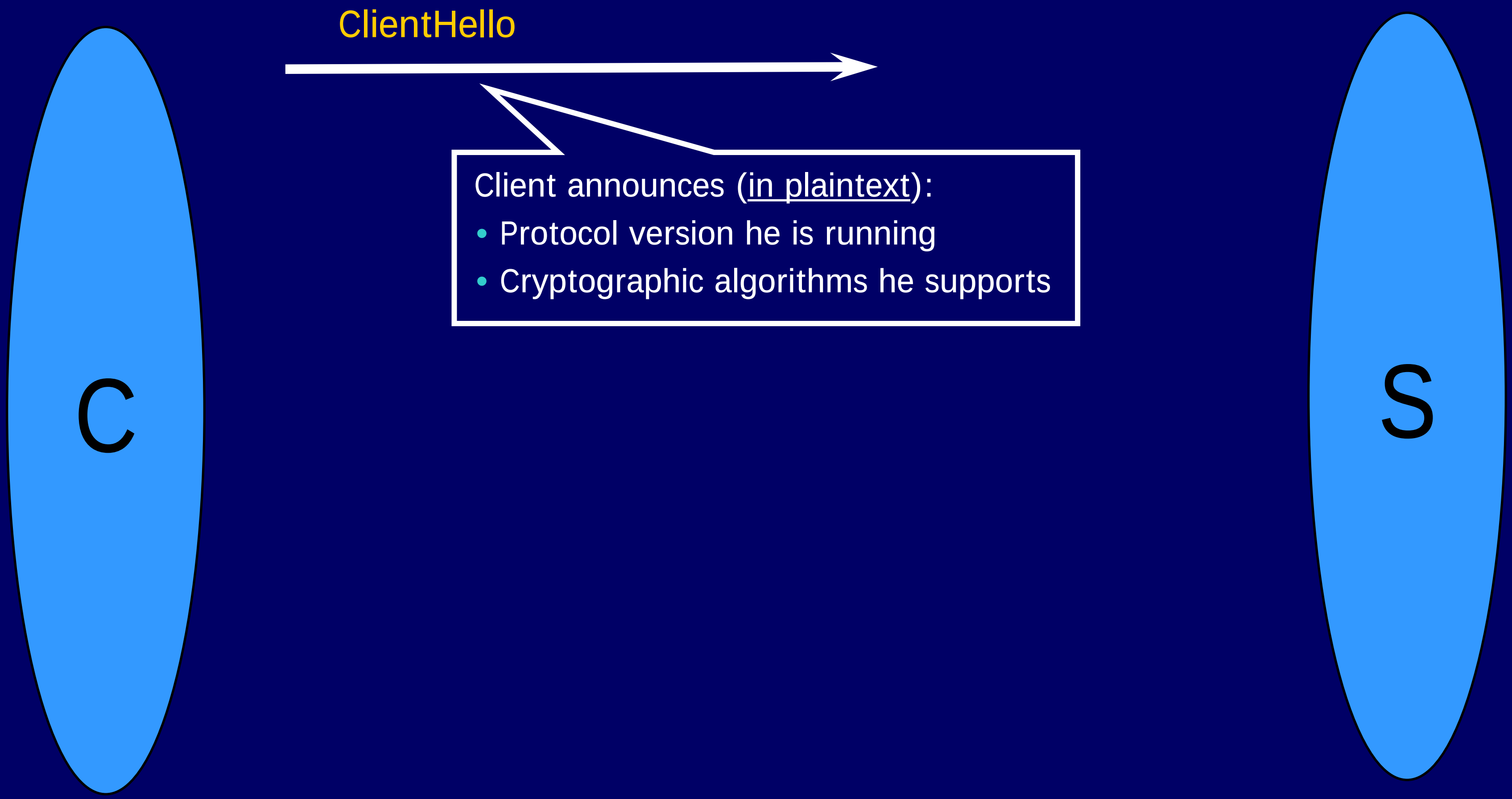
Abbreviated Handshake

- The handshake protocol may be executed in an abbreviated form to resume a previously established session
  - No authentication, key material not exchanged
  - Session resumed from an old state
- For complete analysis, have to model both full and abbreviated handshake protocol
  - This is a common situation: many protocols have several branches, subprotocols for error handling, etc.

Rational Reconstruction

- Begin with simple, intuitive protocol
  - Ignore client authentication
  - Ignore verification messages at the end of the handshake protocol
  - Model only essential parts of messages (e.g., ignore padding)
- Execute the model checker and find a bug
- Add a piece of TLS to fix the bug and repeat
  - Better understand the design of the protocol

Protocol Step by Step: ClientHello



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

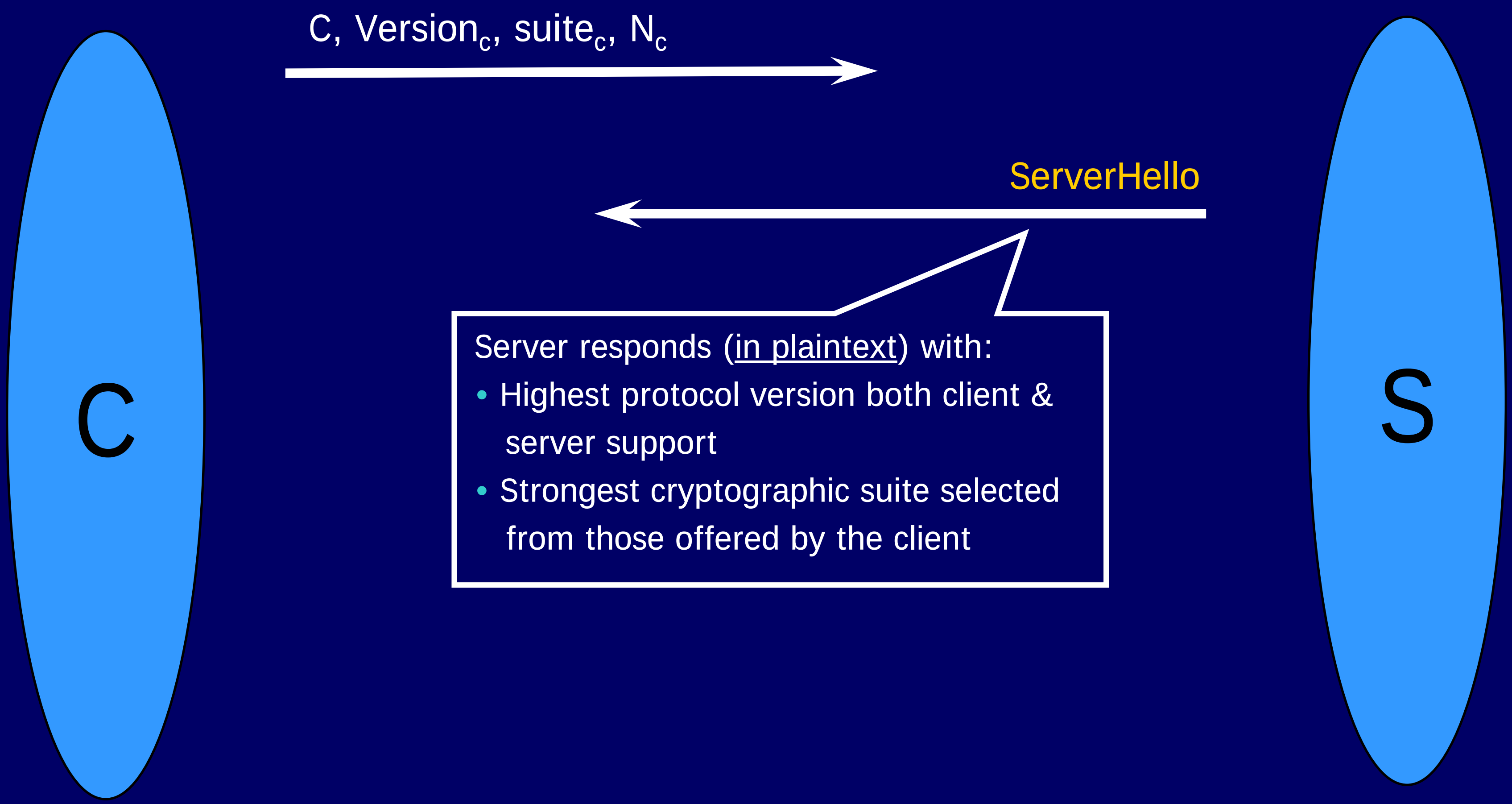
Session id (if the client wants to resume an old session)

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

ClientHello (Murφ)

```
ruleset i: ClientId do
  ruleset j: ServerId do
    rule "Client sends ClientHello to server (new session)"
      cli[i].state = M_SLEEP &
      cli[i].resumeSession  = false
    ==>
    var
      outM: Message;  -- outgoing message
    begin
      outM.source := i;
      outM.dest := j;
      outM.session := 0;
      outM.mType := M_CLIENT_HELLO;
      outM.version := cli[i].version;
      outM.suite := cli[i].suite;
      outM.random := freshNonce();
      multisetadd (outM, cliNet);
      cli[i].state  := M_SERVER_HELLO;
    end;
  end;
end;
```

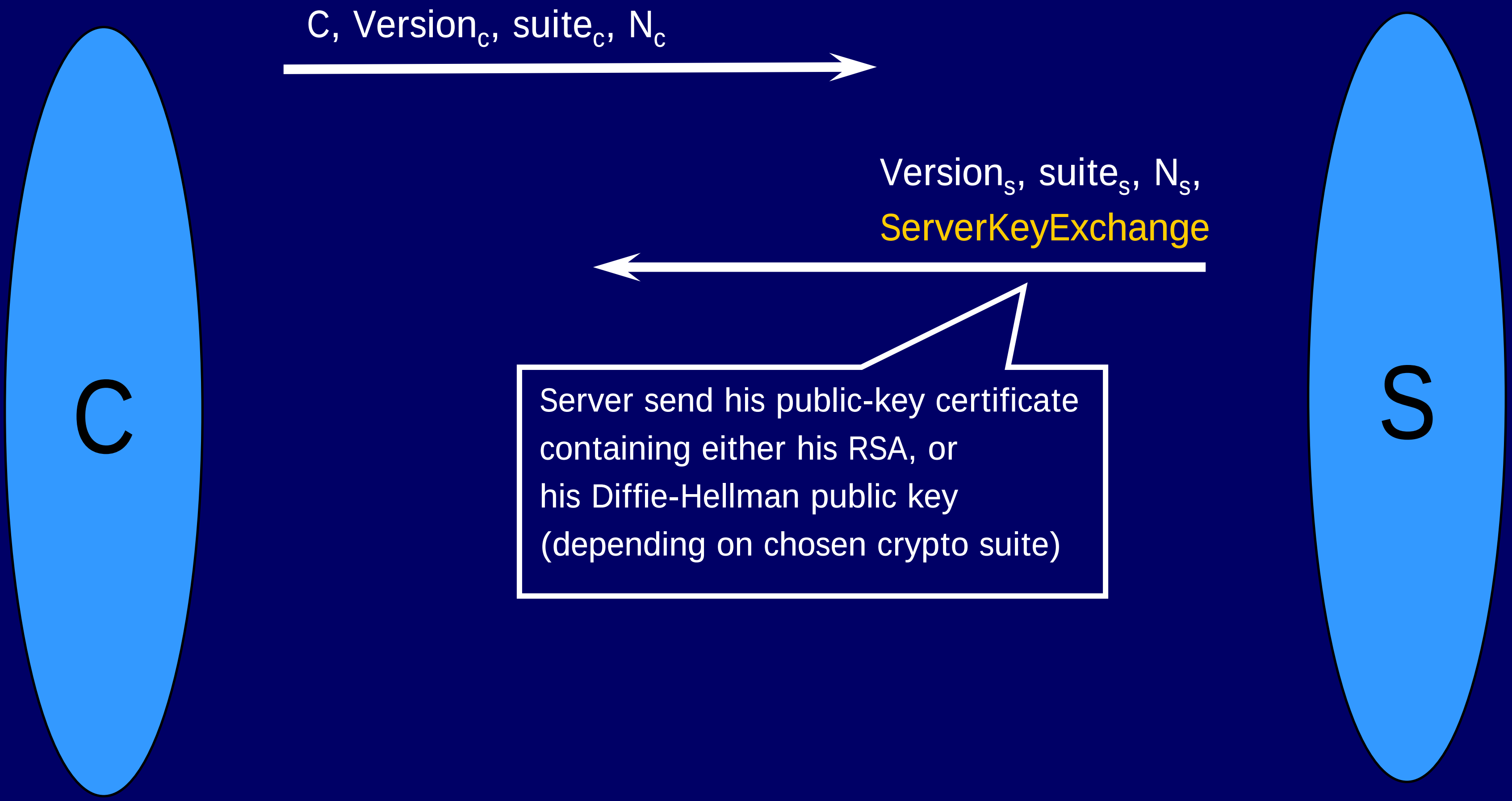
ServerHello



ServerHello (Murφ)

```
ruleset i: ServerId do
  choose l: serNet do
   rule “Server receives ServerHello (new session)"
      ser[i].clients[0].state = M_CLIENT_HELLO &
      serNet[l].dest = i &
      serNet[l].session = 0
    ==>
    var
       inM:   Message;   -- incoming message
       outM: Message;   -- outgoing message
    begin
      inM := serNet[l];  -- receive message
      if inM.mType = M_CLIENT_HELLO then
         outM.source := i;
         outM.dest := inM.source;
         outM.session := freshSessionId();
         outM.mType := M_SERVER_HELLO;
         outM.version := ser[i].version;
         outM.suite := ser[i].suite;
         outM.random := freshNonce();
         multisetadd (outM, serNet);
         ser[i].state  := M_SERVER_SEND_KEY;
    end;  end;  end;
```

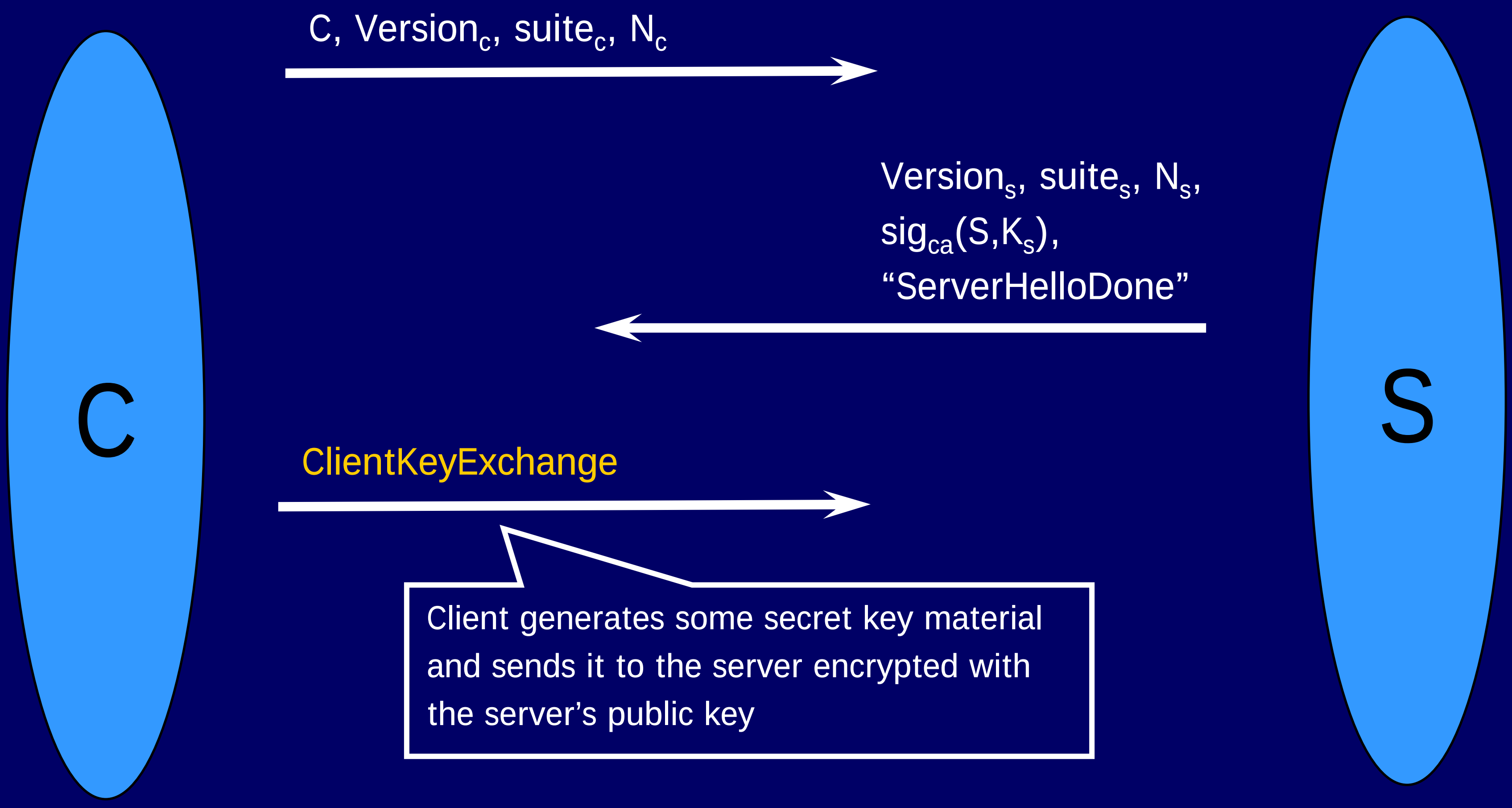
ServerKeyExchange



“Abstract” Cryptography

- We will use abstract data types to model cryptographic operations
  - Assumes that cryptography is perfect
  - No details of the actual cryptographic schemes
  - Ignores bit length of keys, random numbers, etc.
- Simple notation for encryption, signatures, hashes
  - $\{M\}_k$ is message M encrypted with key k
  - $sig_k(M)$ is message M digitally signed with key k
  - $hash(M)$ for the result of hashing message M with a cryptographically strong hash function

ClientKeyExchange

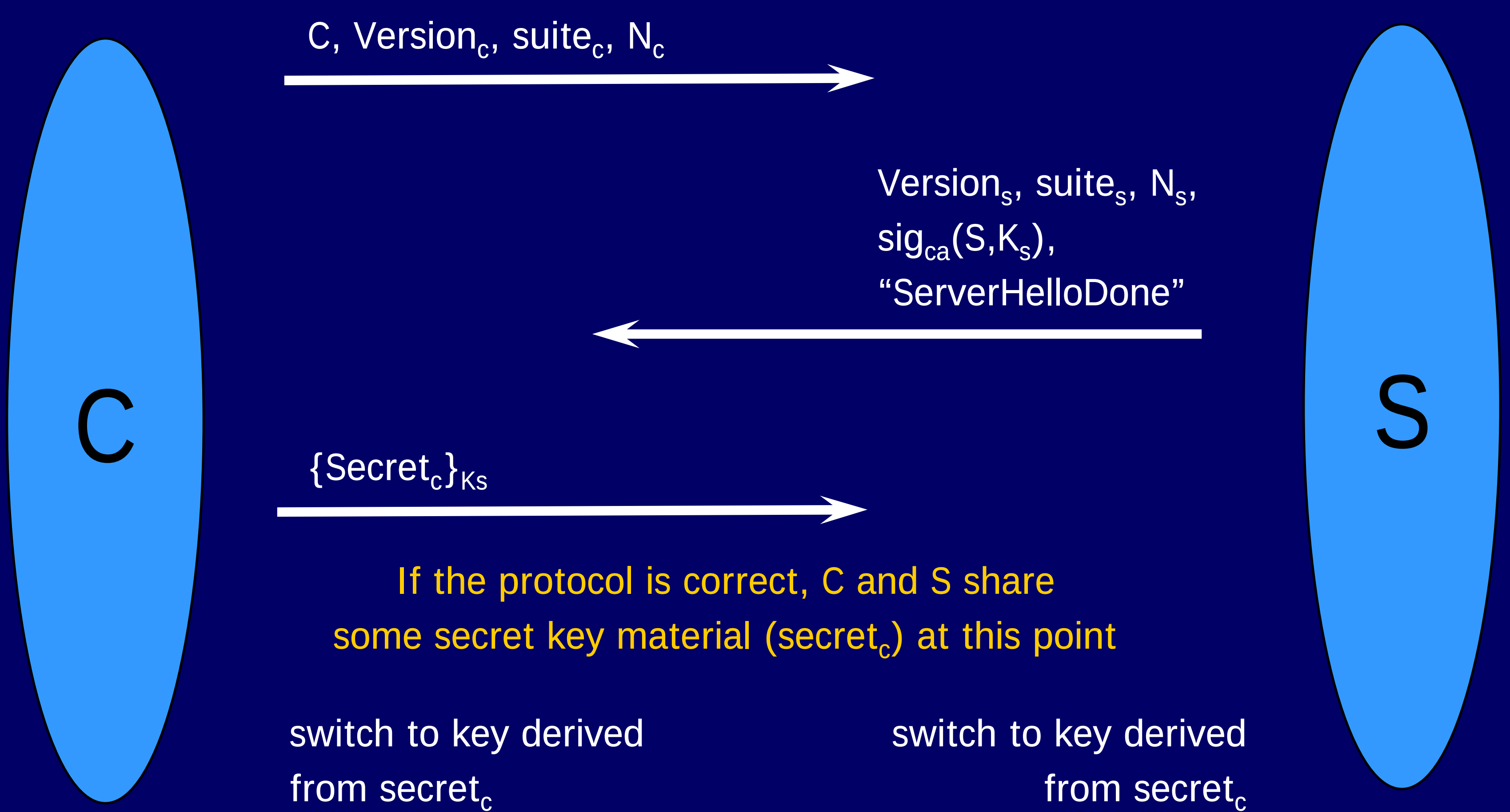


ClientKeyExchange (RFC)

Let's model this as $\{Secret_c\}_{Ks}$

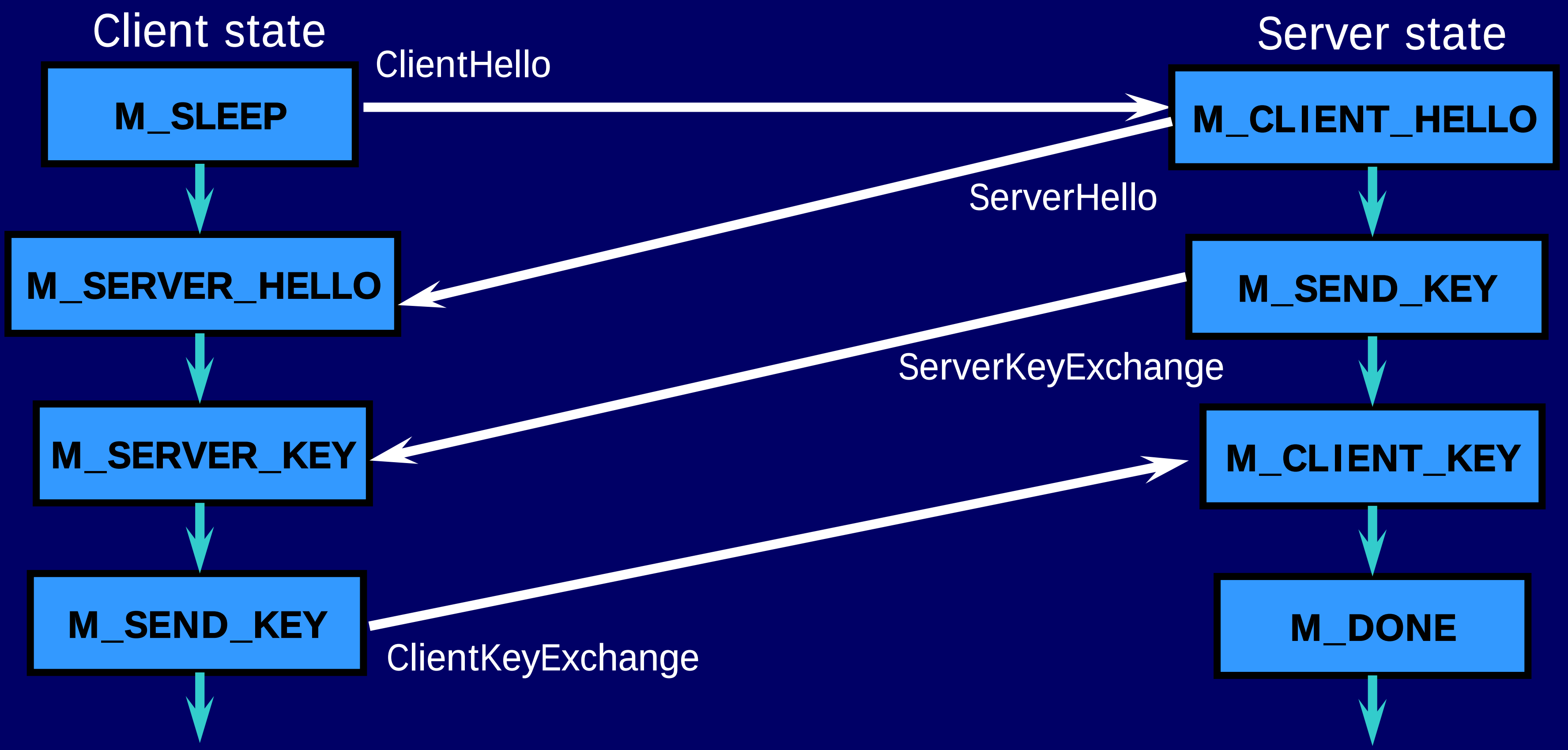
```
struct {
   select (KeyExchangeAlgorithm) {
      case rsa: EncryptedPreMasterSecret;
      case diffie_hellman: ClientDiffieHellmanPublic;
   } exchange_keys
} ClientKeyExchange

struct {
   ProtocolVersion client_version;
   opaque random[46];
} PreMasterSecret
```

“Core” TLS

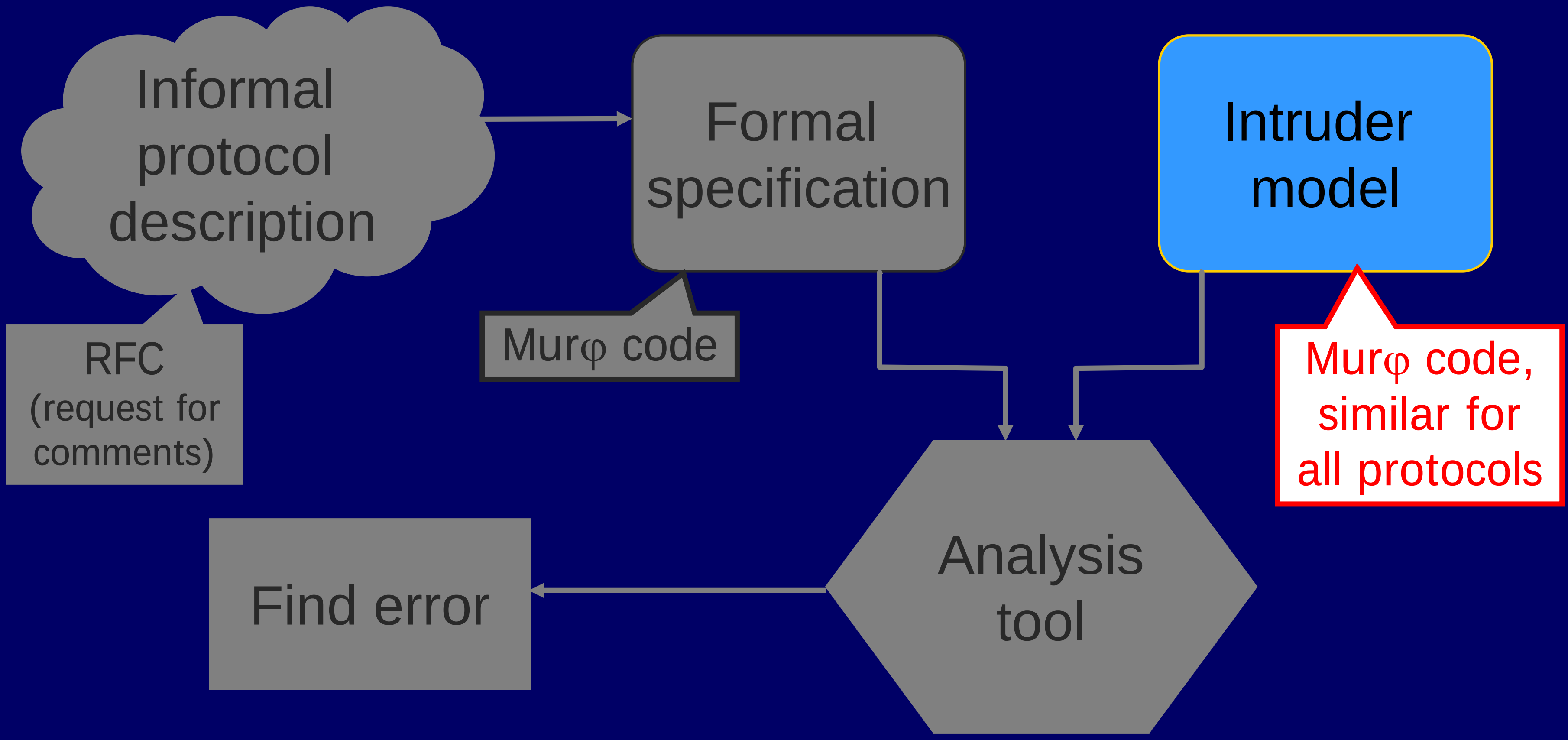

C, $Version_c$, $suite_c$, N_c
$Version_s$, $suite_s$, N_s,
$sig_{ca}(S,K_s)$,
“ServerHelloDone”
$\{Secret_c\}_{Ks}$
C
S
If the protocol is correct, C and S share
some secret key material ($secret_c$) at this point
switch to key derived
from $secret_c$
switch to key derived
from $secret_c$

Participants as Finite-State Machines

Murφ rules define a finite-state machine for each protocol participant



Intruder Model



Intruder Can Intercept

- Store a message from the network in the data structure modeling intruder's "knowledge"

```
ruleset i: IntruderId do
  choose l: cliNet do
    rule "Intruder intercepts client's message"
      cliNet[l].fromIntruder = false
    ==>
    begin
      alias msg: cliNet[l] do   -- message from the net
      ...
      alias known: int[i].messages do
         if multisetcount(m: known,
                          msgEqual(known[m], msg)) = 0 then
            multisetadd(msg, known);
         end;
      end;
    end;
```

Intruder Can Decrypt if Knows Key

- If the key is stored in the data structure modeling intruder's "knowledge", then read message

```
ruleset i: IntruderId do
  choose l: cliNet do
    rule "Intruder intercepts client's message"
      cliNet[l].fromIntruder = false
    ==>
    begin
      alias msg: cliNet[l] do   -- message from the net
      ...
      if msg.mType = M_CLIENT_KEY_EXCHANGE then
           if keyEqual(msg.encKey, int[i].publicKey.key) then
              alias sKeys: int[i].secretKeys do
                if multisetcount(s: sKeys,
                   keyEqual(sKeys[s], msg.secretKey)) = 0 then
                   multisetadd(msg.secretKey, sKeys);
                end;
           end;
      end;
```

Intruder Can Create New Messages

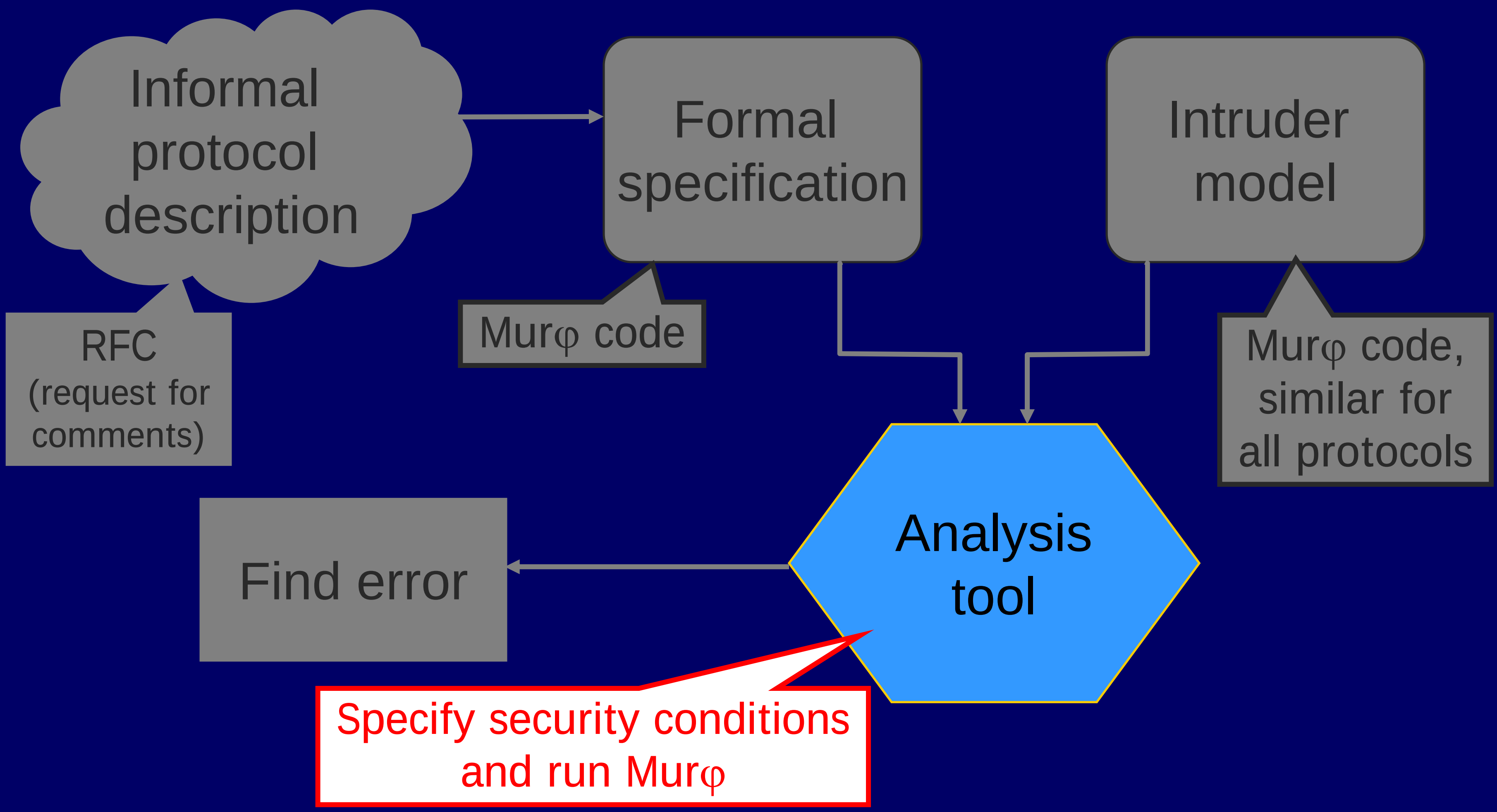
- Assemble pieces stored in the intruder's "knowledge" to form a message of the right format

```
ruleset i: IntruderId do
  ruleset d: ClientId do
    ruleset s: ValidSessionId do
      choose n: int[i].nonces do
      ruleset version: Versions do
      rule "Intruder generates fake ServerHello"
          cli[d].state = M_SERVER_HELLO
        ==>
        var
          outM: Message;  -- outgoing message
        begin
          outM.source := i; outM.dest := d; outM.session := s;
          outM.mType := M_SERVER_HELLO;
          outM.version := version;
          outM.random := int[i].nonces[n];
          multisetadd (outM, cliNet);
        end; end; end; end;
```

Intruder Model and Cryptography

- There is no actual cryptography in this model
  - Messages are marked as “encrypted” or “signed”, and the intruder rules respect these markers
- The assumption that cryptography is perfect is reflected by the absence of certain intruder rules
  - There is no rule for creating a digital signature with a key that is not known to the intruder
  - There is no rule for reading the contents of a message which is marked as “encrypted” with a certain key, when this key is not known to the intruder
  - There is no rule for reading the contents of a “hashed” message

Running Murφ Analysis



Secrecy

- Intruder should not be able to learn the secret generated by the client

```
ruleset i: ClientId do
  ruleset j: IntruderId do
    rule "Intruder has learned a client's secret"
      cli[i].state = M_DONE &
      multisetcount(s: int[j].secretKeys,
         keyEqual(int[j].secretKeys[s], cli[i].secretKey)) > 0
    ==>
    begin
      error "Intruder has learned a client's secret"
    end;
  end;
end;
```

Shared Secret Consistency

- After the protocol has finished, client and server should agree on their shared secret

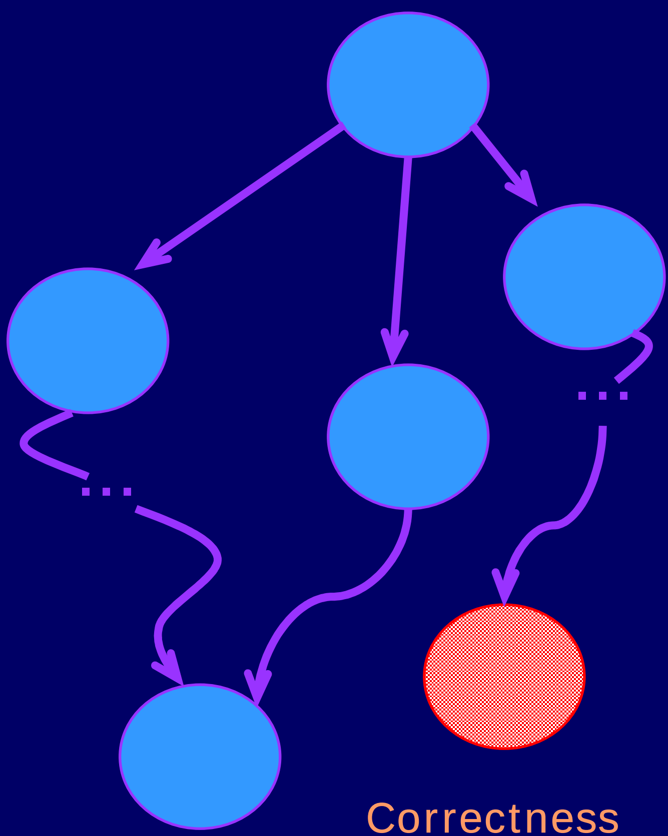
```
ruleset i: ServerId do
  ruleset s: SessionId do
    rule "Server's shared secret is not the same as its client's"
      ismember(ser[i].clients[s].client, ClientId) &
      ser[i].clients[s].state = M_DONE &
      cli[ser[i].clients[s].client].state = M_DONE &
      !keyEqual(cli[ser[i].clients[s].client].secretKey,
                     ser[i].clients[s].secretKey)
    ==>
    begin
      error "S's secret is not the same as C's"
    end;
  end;
end;
```

Version and Crypto Suite Consistency

- Client and server should be running the highest version of the protocol they both support

```
ruleset i: ServerId do
  ruleset s: SessionId do
    rule "Server has not learned the client's version or suite correctly"
      !ismember(ser[i].clients[s].client, IntruderId) &
      ser[i].clients[s].state = M_DONE &
      cli[ser[i].clients[s].client].state = M_DONE &
      (ser[i].clients[s].clientVersion != MaxVersion |
       ser[i].clients[s].clientSuite.text != 0)
    ==>
    begin
      error "Server has not learned the client's version or suite correctly"
    end;
  end;
end;
```

Finite-State Verification

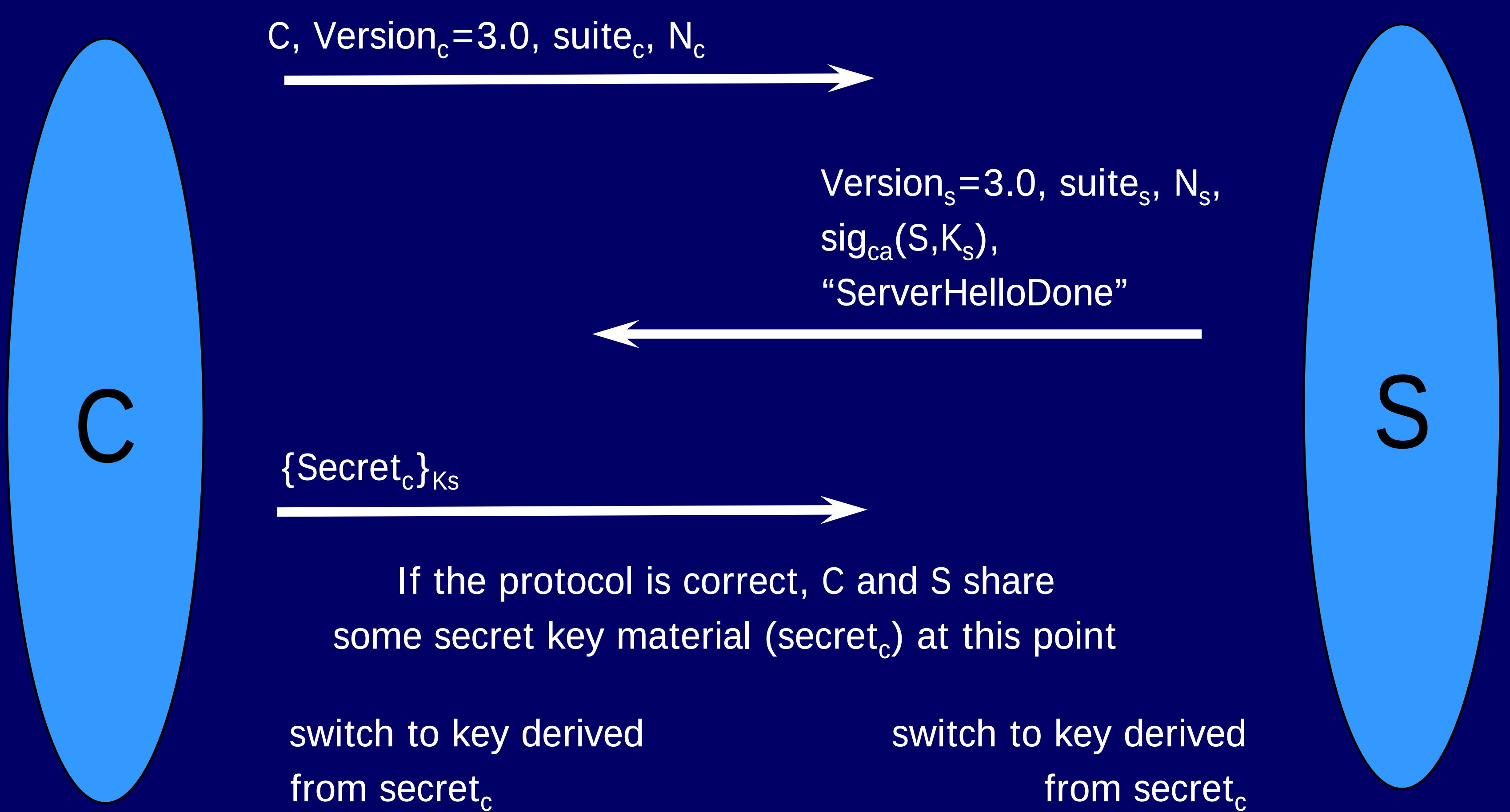


- Murφ rules for protocol participants and the intruder define a nondeterministic state transition graph
- Murφ will exhaustively enumerate all graph nodes
- Murφ will verify whether specified security conditions hold in every reachable node
- If not, the path to the violating node will describe the attack

When Does Murφ Find a Violation?

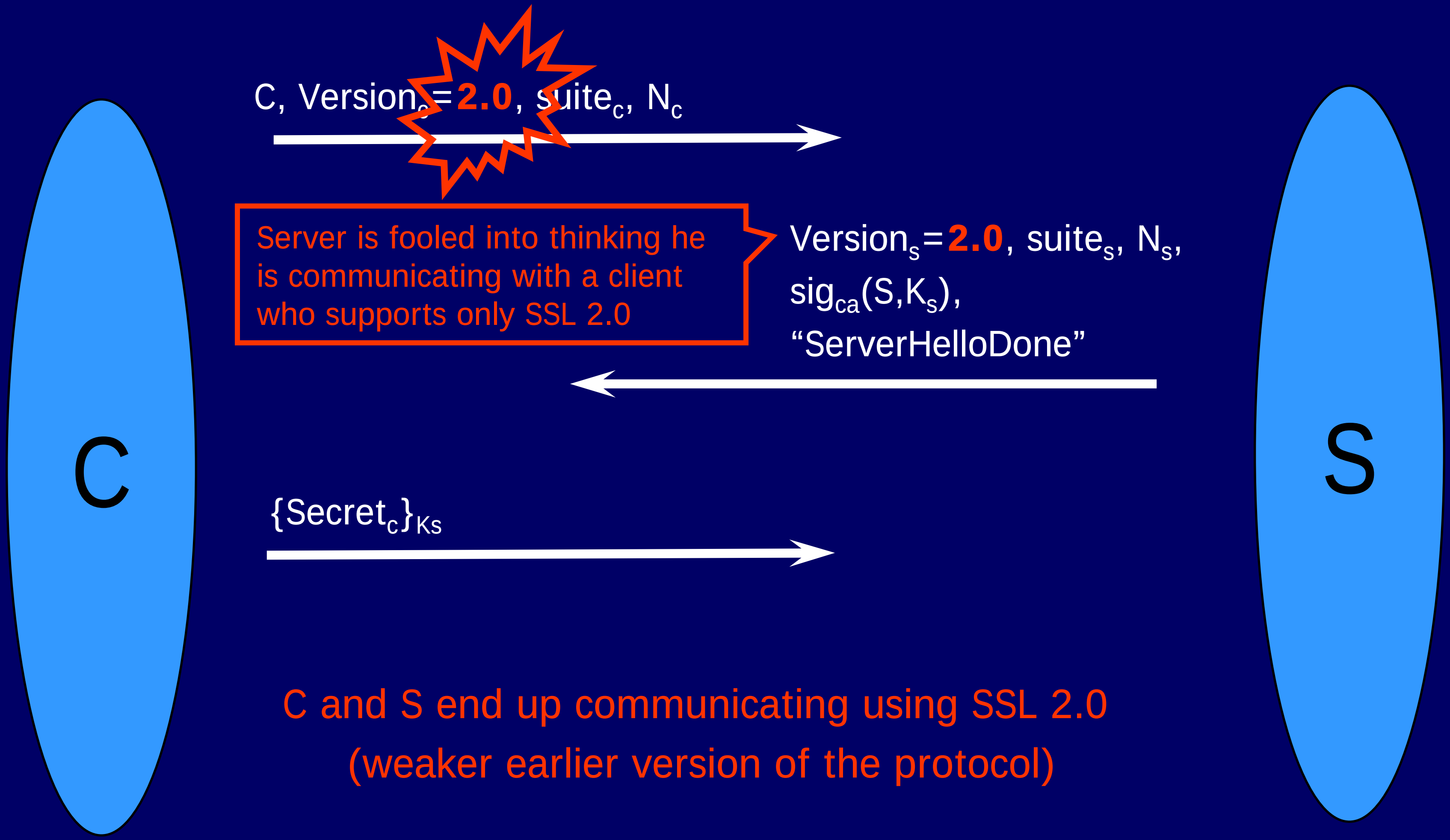
- Bad abstraction
  - Removed too much detail from the protocol when constructing the abstract model
  - Add the piece that fixes the bug and repeat
  - This is part of the rational reconstruction process
- Genuine attack
  - Yay! Hooray!
  - Attacks found by formal analysis are usually quite strong: independent of specific cryptographic schemes, OS implementation, etc.
  - Test an implementation of the protocol, if available

"Core" SSL 3.0



C, $Version_c$=3.0, $suite_c$, N_c
$Version_s$=3.0, $suite_s$, N_s,
$sig_{ca}(S,K_s)$,
"ServerHelloDone"
{$Secret_c$}$_{Ks}$
If the protocol is correct, C and S share
some secret key material ($secret_c$) at this point
switch to key derived
from $secret_c$
switch to key derived
from $secret_c$
C
S

Version Consistency Fails!



A Case of Bad Abstraction

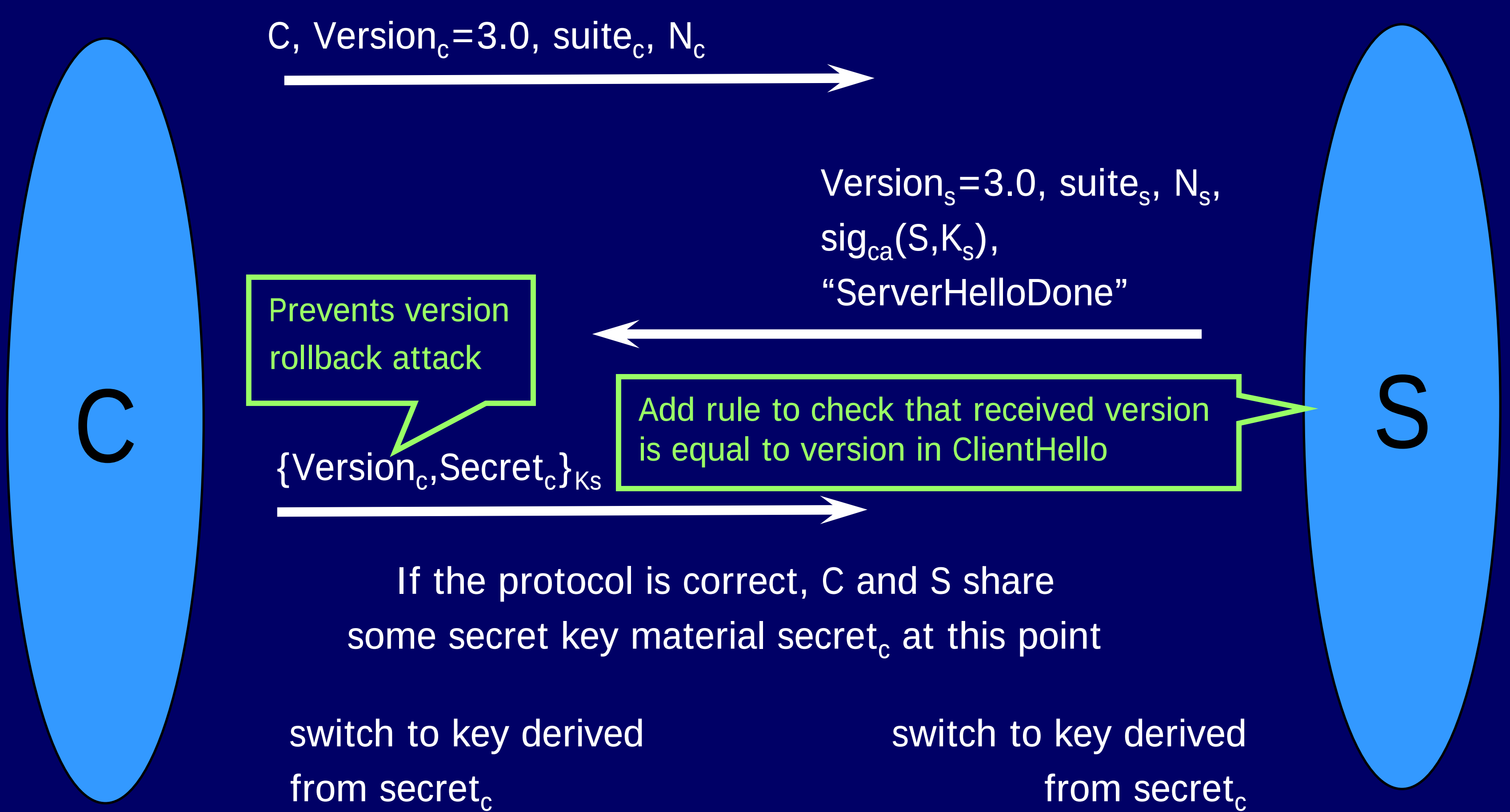
```
struct {
  select (KeyExchangeAlgorithm) {
    case rsa: EncryptedPreMasterSecret;
    case diffie_hellman: ClientDiffieHellmanPublic;
  } exchange_keys
} ClientKeyExchange
```

Model this as $\{Version_c, Secret_c\}_{Ks}$

This piece matters! Need to add it to the model.

```
struct {
  ProtocolVersion client_version;
  opaque random[46];
} PreMasterSecret
```

Fixed "Core" SSL 3.0



SSL 2.0 Weaknesses (Fixed in 3.0)

- Cipher suite preferences are not authenticated
  - "Cipher suite rollback" attack is possible
- Weak MAC construction
- 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

Basic Pattern for Doing Your Project

- Read and understand protocol specification
  - Typically an RFC or a research paper
  - Website has some protocol specs, I'll put up more
- Choose a tool
  - Murφ by default, but I'll describe many other tools
  - Play with Murφ now to get some experience (installing, running simple models, etc.)
- Start with a simple (possibly flawed) model
  - Rational reconstruction is a good way to go
- Give careful thought to security conditions

Background Reading on SSL 3.0

Optional, for deeper understanding of SSL / TLS

- D. Wagner and B. Schneier. “Analysis of the SSL 3.0 protocol.” USENIX Electronic Commerce ’96.
  - Nice study of an early proposal for SSL 3.0
- J.C. Mitchell, V. Shmatikov, U. Stern. “Finite-State Analysis of SSL 3.0”. USENIX Security ’98.
  - Murφ analysis of SSL 3.0 (similar to this lecture)
  - Actual Murφ model is in /projects/shmat/Murphi3.1/ex/secur
- D. Bleichenbacher. “Chosen Ciphertext Attacks against Protocols Based on RSA Encryption Standard PKCS #1”. CRYPTO ’98.
  - Cryptography is <u>not</u> perfect: this paper breaks SSL 3.0 by directly attacking underlying implementation of RSA