# Using Interface Specifications for Verifying Cryptoprotocol Implementations

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# Crypto-Protocol Analysis

State of the affairs:

A *lot* of very successful work in formally verifying abstract models of crypto-protocol design.

- virtually every formal method has been applied
- seemingly more people working on verification than on designing protocols
- efficient tool-support usable by academics or specialists
- sometimes used at industrial size protocols (usually by tool developers themselves)

(Almost) solves the problem whether design is secure.

# Problem

How do I know a crypto-protocol implementation is secure ?

Possible solution:

Verify design model, write code generator, verify code generator.

Problems:

- very challenging to verify code generator
- generated code satisfactory for given requirements (maintainability, performance, size, …) ?
- not applicable to existing implementations

# Alternative Solution

Verify implementation against verified design or directly against security requirements.

So far applied to self-written or restricted code.

Surprisingly few approaches so far:

- J. Jürjens, M. Yampolski (ASE´05): methodology + initial results for restricted C code
- J. Goubault-Larrecq, F. Parrennes (VMCAI´05): self-coded client-side of Needham-Schroeder in C
- K. Bhargavan, C. Fournet, A. Gordon (CSFW´06): self-coded implementations in F-sharp

May reduce first problem. How about other two ?

# Towards Verifying Legacy Implementations

Goal: Verify implementation created independently.

Options:

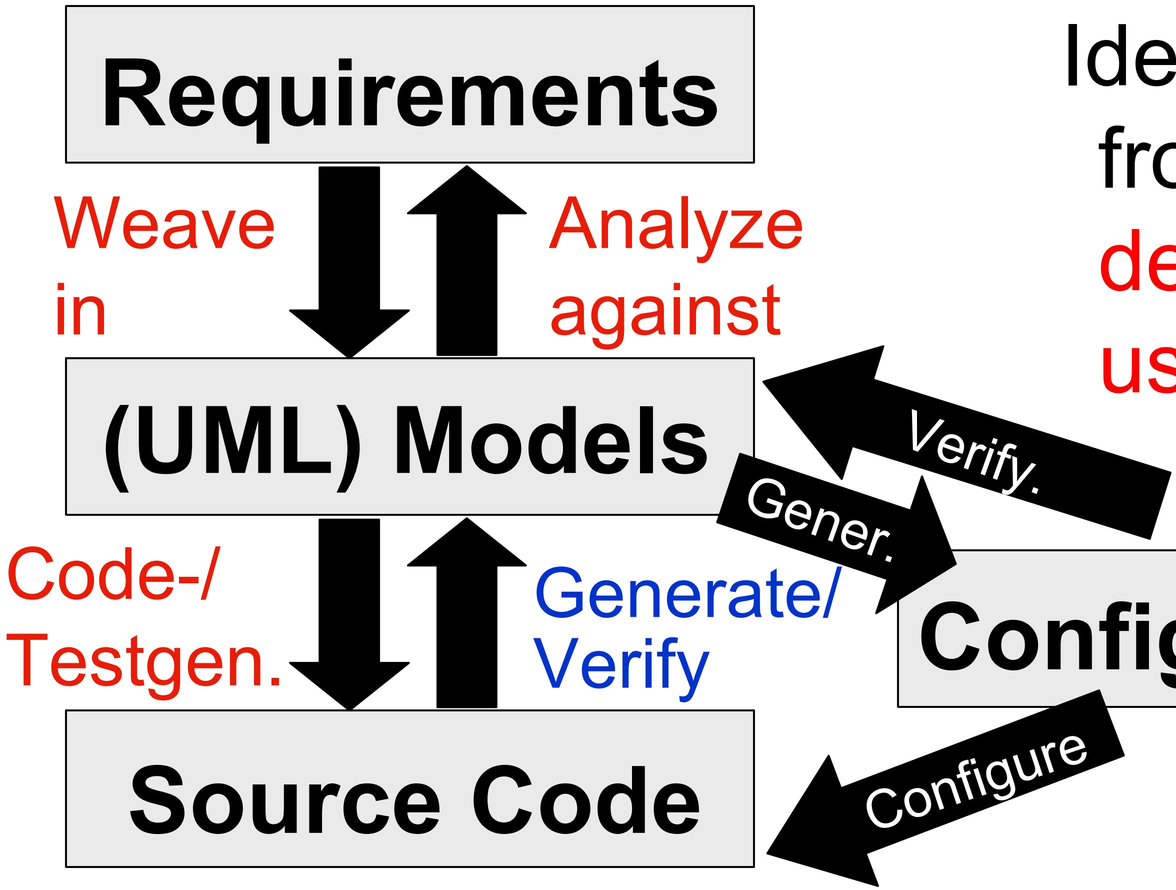
3) Generate models from code and verify these.

- Advantages: Seems more automatic. Users in practice can work on familiar artifact (code), don´t need to otherwise change development process (!).
- Challenges: Currently possible for restricted code or using significant annotations. Need to verify model generator.

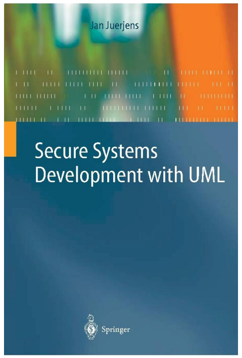
2) Create models and code manually and verify code against models.

- Advantages: Split heavy verification burden. Get some verification result already in design phase (for non-legacy implementations).

# Background: Model-based Security Engineering




Idea: Extract models from artefacts in development and use of software.




➔ Long-term goal: Tool-supported, theoretically sound, efficient automated security design & analysis.

# Why Behavioural Interfaces ?

Goal: verify implementations of significant complexity automatically and exhaustively against non-trivial requirements.

Have software model-checkers, but so far not used for very complex implementations and very sophisticated requirements (e.g. involving Dolev-Yao type attacker models).

Do have powerful type checkers.

Idea: push the envelope by introducing behaviour into types ➔ behavioural interfaces

Long line of foundational work (rely/guarantee etc.), some tools (SLAM, Blast)

# Interface based Security Analysis in FOL

Based on usual Dolev-Yao model.

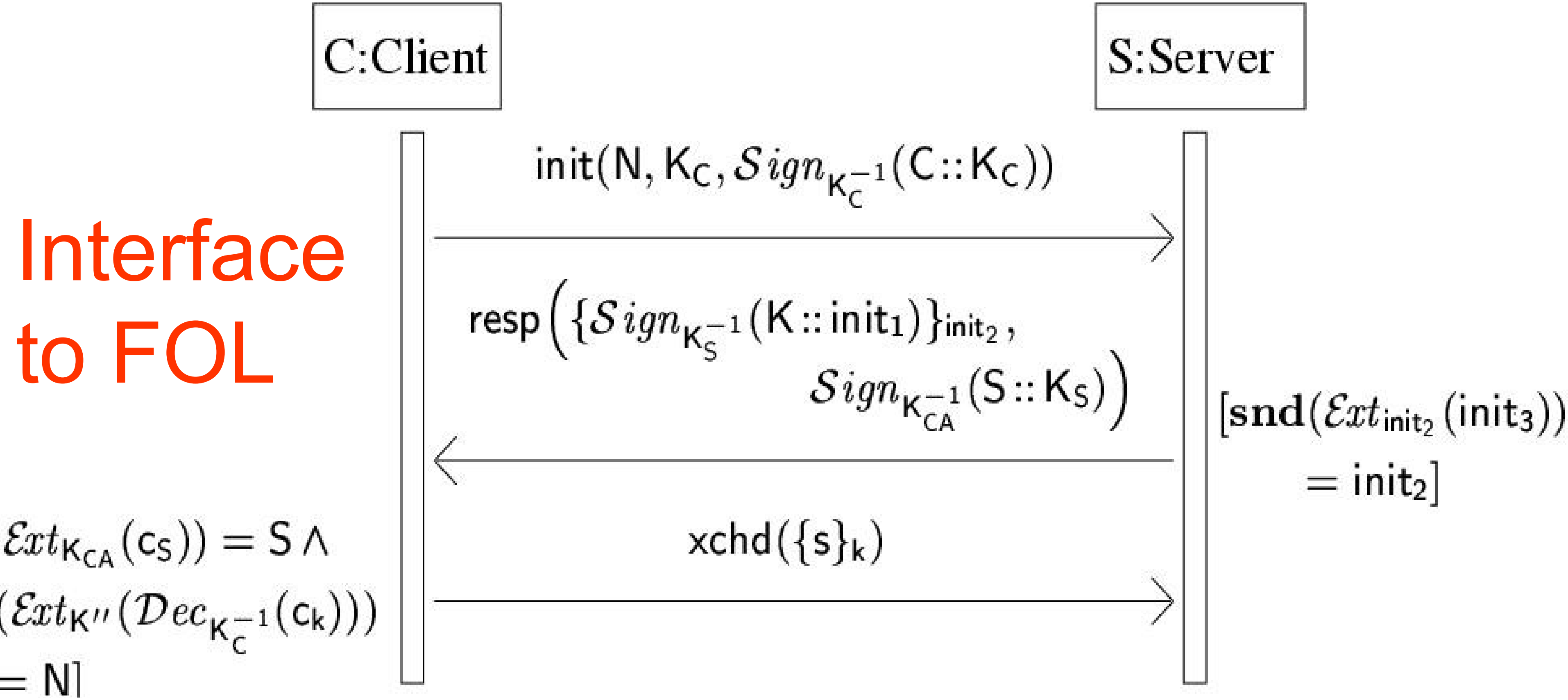
Approximate adversary knowledge set from above:

Predicate *knows(E)* meaning that adversary may get to know *E* during the execution of the system.

E.g. secrecy requirement:

For any secret *s*, check whether can derive *knows(s)* from model-generated formulas using automatic theorem prover. [ICSE05]

# Interface to FOL




$$knows(N) \wedge knows(K_C) \wedge knows(Sign_{K_C^{-1}}(C::K_C))$$

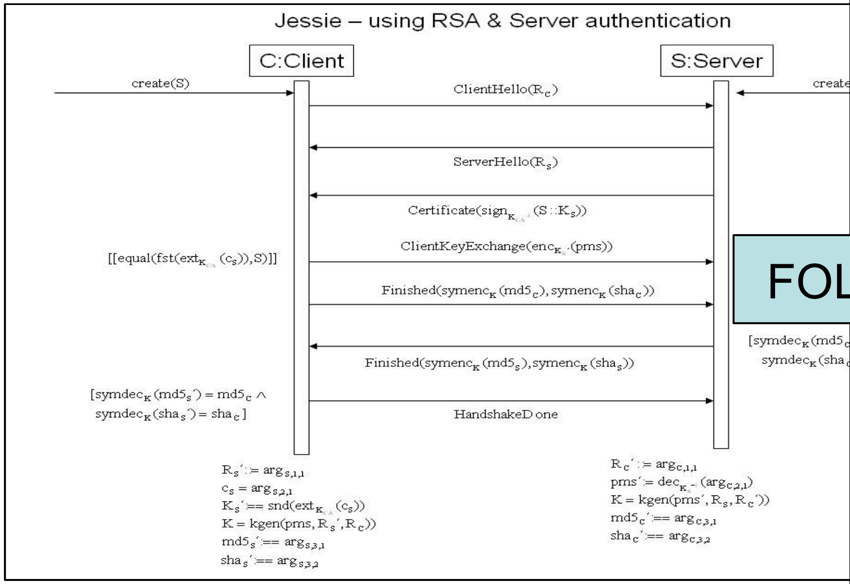
$$\wedge\ \forall init_1, init_2, init_3.[knows(init_1) \wedge knows(init_2) \wedge$$

$$knows(init_3) \wedge snd(Ext_{init_2}(init_3)) = init_2$$

$$\Rightarrow knows(\{Sign_{K_S^{-1}}(\ldots)\}_{\ldots}) \wedge [knows(Sign\ldots)]$$

$$\wedge\ \forall resp_1, resp_2.[\ldots \Rightarrow \ldots]]$$

# Interface Model Verification




FOL

```
...
((
  knows(ArgC_3)
  & (equal(fst(ArgC_3), type_serverkeyexchange))
  & (equal(snd(ext(snd(snd(ArgC_3)), k_ca)), skey))
  & (equal(snd(ext(snd(ArgC_2), k_ca)), fst(snd(ArgC_3))))
)
=>(
  ((knows(ArgC_4_1)
    & equal(ArgC_4_1, type_serverhellodone))
    =>(
  ( ( true & equal(ClientKeyExchange, enc(premasterkey, skey)
)
...
%------------------------ Conjecture --

input_formula(attack,conjecture,(
    knows(mastersecret) )).
```

ATP

```
analyzing results ...
model found/total failure
time limit information: 19 total / 18 strategy
(leaving wrapper).
task myUML_PID1491 on atbroy1 has status SUCCESS
(model found by strategy 300) consuming 1 seconds
deleting temporary files.
e-SETHEO done. exiting
```

Check whether can derive *knows(s)*.

If yes, generate attack scenario.

If no, *s* secret (wrt our attacker).

# Just an Exercise in Code Verification ?

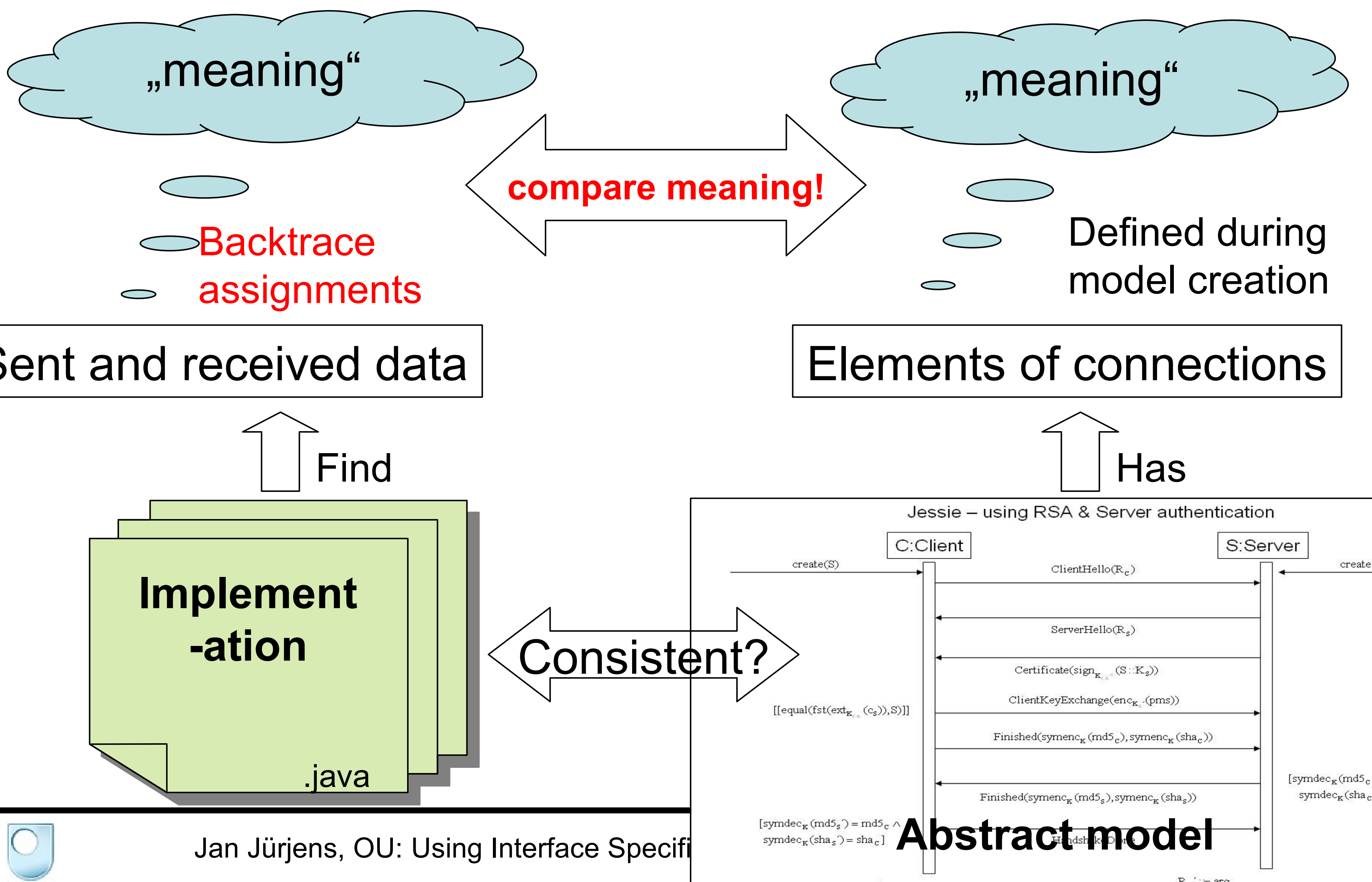
State of the art in practical code verification: execution exploration by testing (possibly generated from models). Limitations:

- For highly interactive systems usually only partial test coverage due to test-space explosion.
- Cryptography inherently un-testable since resilient to brute-force attack.

General approaches to formal software verification exist (Isabelle et al), but limited use by (civilian) software engineers, and usually not for sophisticated properties like Dolev-Yao security.

➔ Develop specialized verification approach.

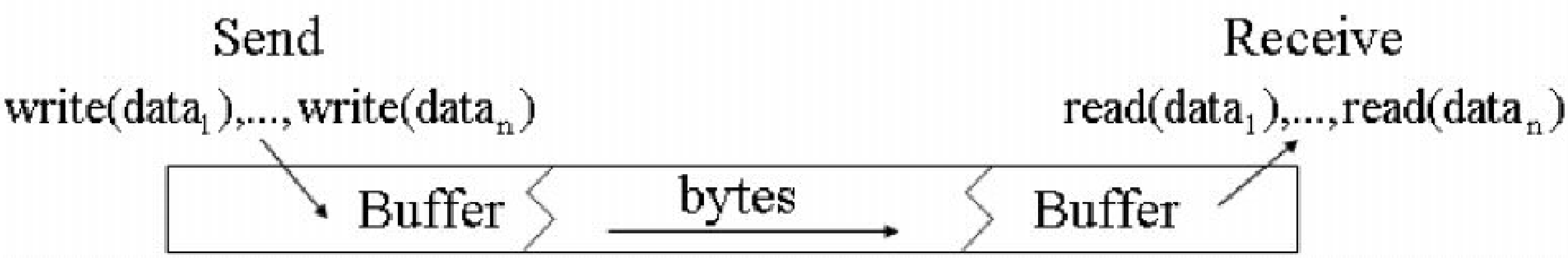
# Interface: Model vs. Implementation



# Input / Output

To extract input/output labels for state machine transitions, analyze input / output mechanism used in the implementation.

Many implementations (e.g. Jessie and JSSE) use buffered communication where the message objects implement read and write methods. Translate these method calls to input / output labels (need to track successive subcalls).



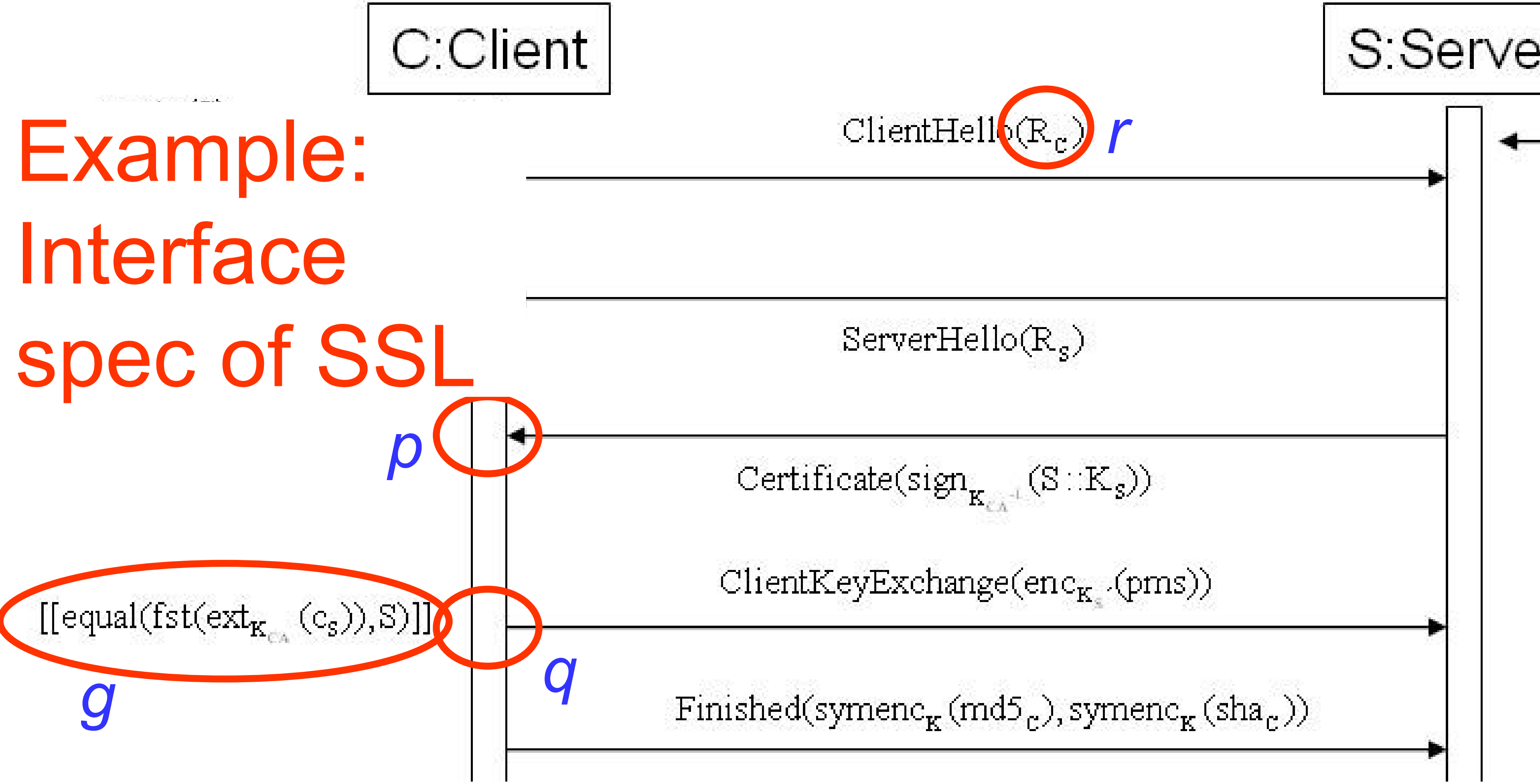
# Example

Sending a protocol message (e.g. ClientHello):

- create the clientHello object with appropriate message parameters
- create the message object msg by giving the clientHello object as an argument
- call the write method at the msg object

```
ClientHello clientHello = new ClientHello(session.protocol,clientRandom,sessionId,
                                          session.enabledSuites,comp, extensions);
Handshake msg = new Handshake(Handshake.Type.CLIENT_HELLO, clientHello);
msg.write (dout, version);
```

# Example: Interface spec of SSL




I) Identify program points:

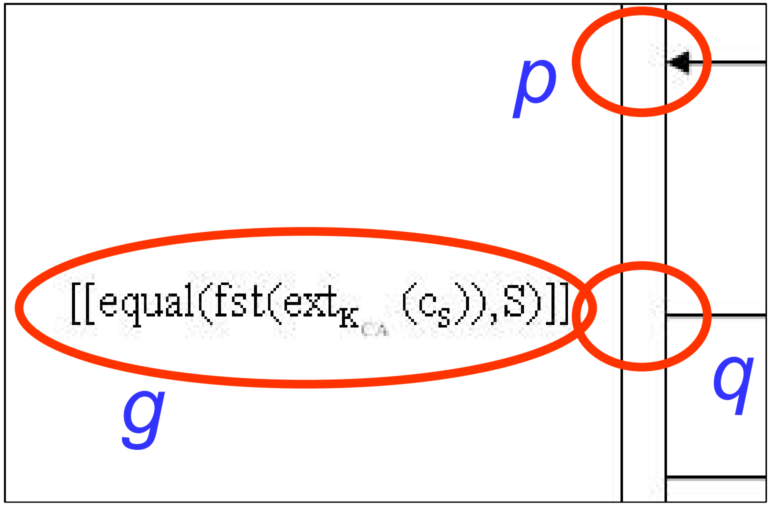
value (*r*), receive (*p*), guard (*g*), send (*q*)

II) Check guards enforced

# Checking Guards

Guard *g* enforced by code?

b) Generate runtime check for *g* at *q* from diagram: simple + effective, but performance penalty.

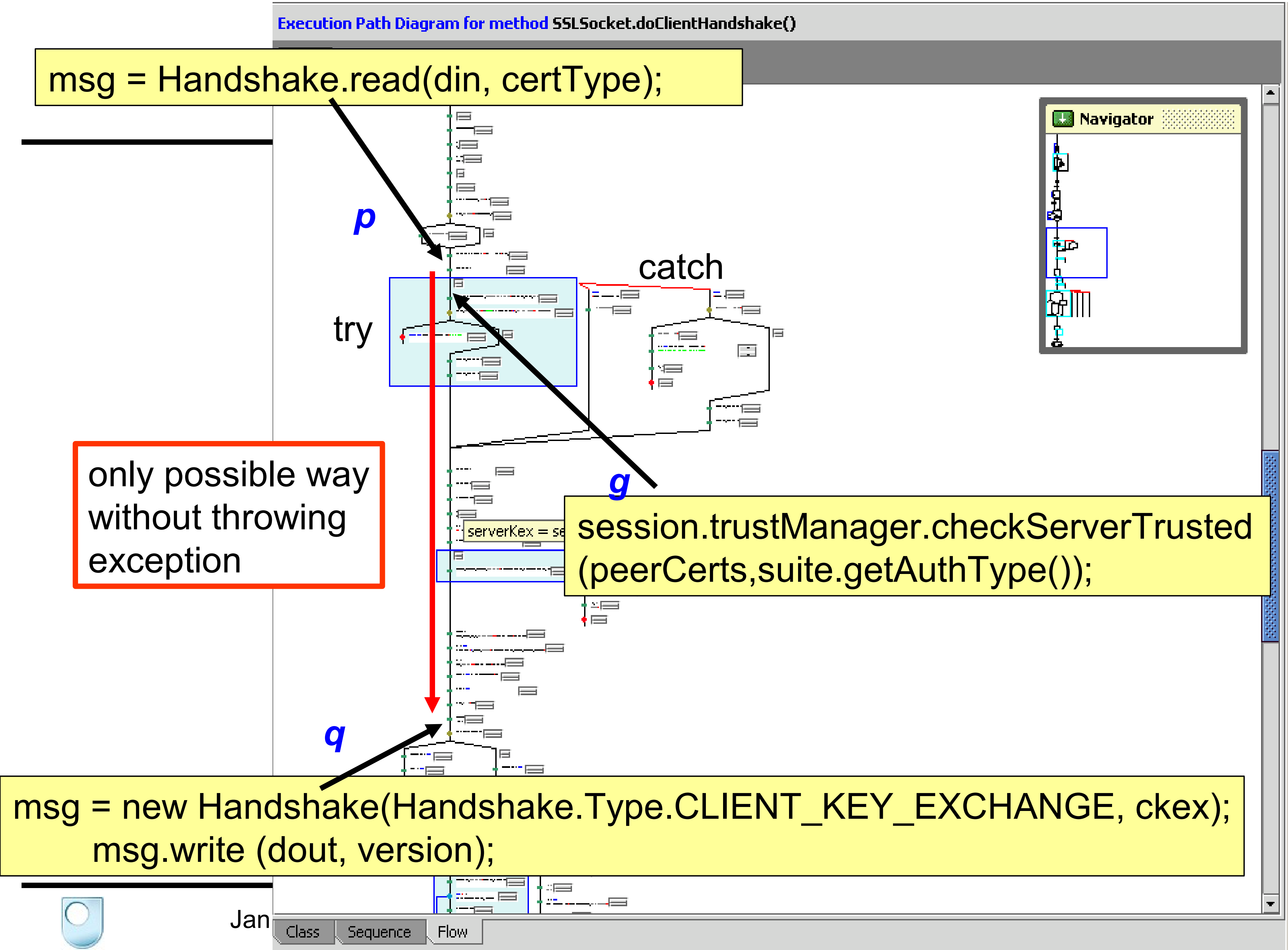



c) Testing against checks (symbolic abstractions for crypto).

[ICFEM02]

d) Automated formal local verification: conditionals between *p* and *q* logically imply *g* (uses Prolog).

[ASE06]


Execution Path Diagram for method SSLSocket.doClientHandshake()
msg = Handshake.read(din, certType);
p
try
catch
Navigator
only possible way without throwing exception
g
serverKex = se
session.trustManager.checkServerTrusted (peerCerts,suite.getAuthType());
q
msg = new Handshake(Handshake.Type.CLIENT_KEY_EXCHANGE, ckex);
msg.write (dout, version);
Class
Sequence
Flow

# Modular Verification with Interfaces

For program fragment p implementing a given interface, generate set of statements derive(L,C,E) such that adversary knowledge is contained in every set K that:

- for every list l of values for the variables in L that satisfy the conditions in C contains the value constructed by instantiating the variables in the expression E with the values from l

When considering single protocol run, can construct finite set of such statements similar to FOL formulas from security analysis.

# Modular Verification: Formalisation

send: represents send command

$g$: FOL formula with symbols $\mathrm{msg}_n$ representing $n^{th}$ argument of message received before program fragment $p$ is executed

$[d]\ p \vDash g$ : $g$ checked in any execution of $p$ initially satisfying $d$ before any send

write $p \vDash g$ for $[\mathrm{true}]\ p \vDash g$.

$$\frac{}{[\mathrm{d}]\ \mathsf{if}\ c\ \mathsf{then}\ p\ \mathsf{else}\ q \models g}\,(c \wedge d \Rightarrow g,\ \mathsf{no\ send\ in}\ q)$$

# Modular Verification: Some Rules

$$\frac{}{[\mathsf{d}]\ \ \mathsf{if}\ \ c\ \ \mathsf{then}\ \ p\ \ \mathsf{else}\ \ q \models g}(c \wedge d \Rightarrow g,\ \mathsf{no\ send\ in}\ q)$$

$$\frac{}{[\mathsf{d}]\ \ \mathsf{if}\ \ c\ \ \mathsf{then}\ \ p\ \ \mathsf{else}\ \ q \models g}(\neg c \wedge d \Rightarrow g,\ \mathsf{no\ send\ in}\ p)$$

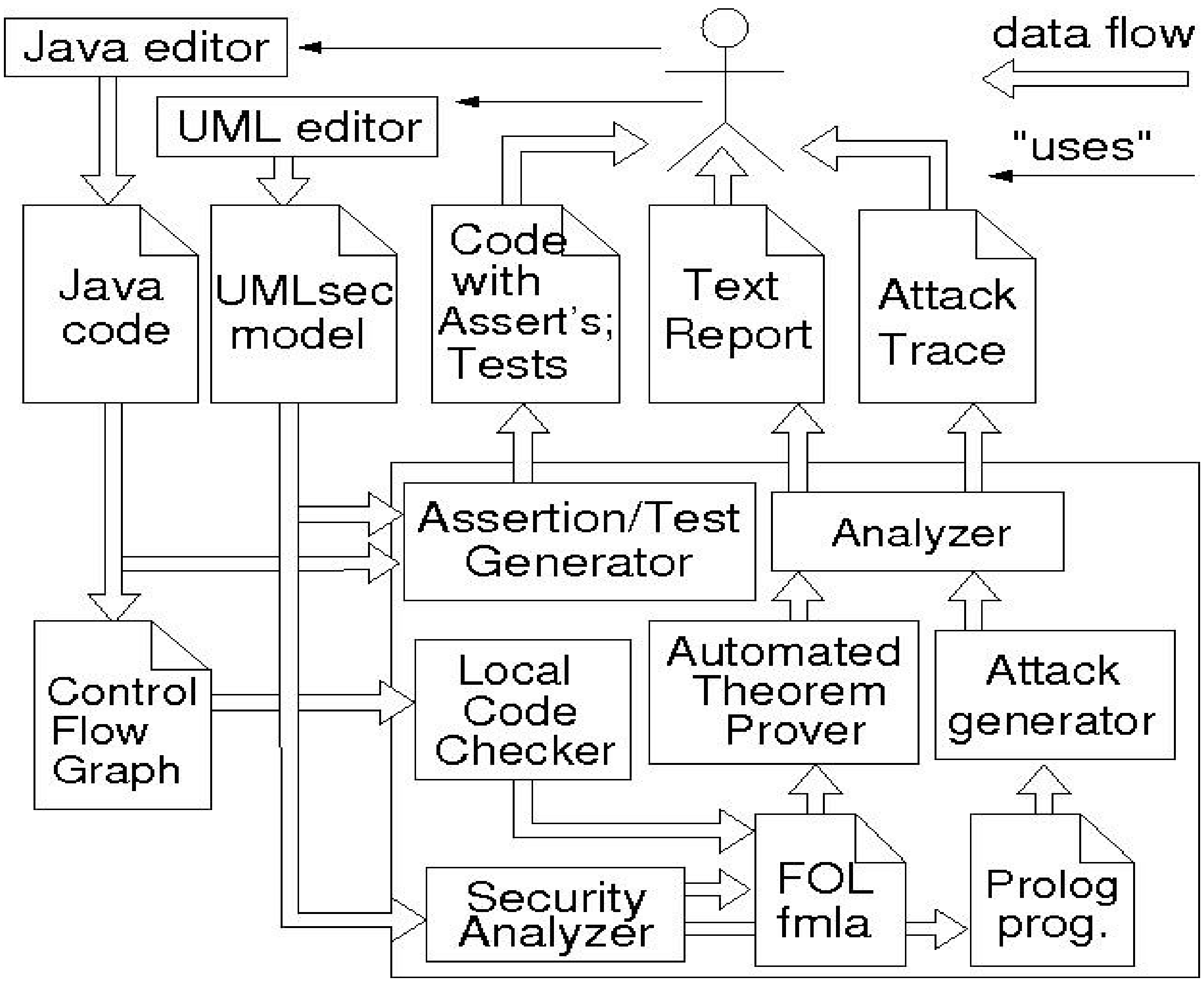
$$\frac{[d]p \models g}{[\mathsf{d}]\ \ \mathsf{if}\ \ c\ \ \mathsf{then}\ \ p\ \ \mathsf{else}\ \ q \models g}(d \Rightarrow c) \qquad \frac{[d]p \models g}{[d]p;q \models g}$$

$$\frac{[d]q \models g}{[\mathsf{d}]\ \ \mathsf{if}\ \ c\ \ \mathsf{then}\ \ p\ \ \mathsf{else}\ \ q \models g}(d \Rightarrow \neg c) \qquad \frac{[d]p \models g}{[d']p \models g} d' \Rightarrow d$$

$$\frac{[d]p \models g}{x := e;p \models g} d \Rightarrow x = e$$

# Tool Support

[FASE05,ICSE06,ASE07, STTT07,ICSE08]




Also:

- configuration analysis: (user permissions, firewall rules/ policies) [FASE08]
- code traceability (with Yijun Yu)

Open-source

# Some Applications

Analyzed designs / implementations / configurations e.g. for

- Biometry- or smart-card-based identification
- authentication (crypto protocols)
- authorization (user permissions, e.g. SAP systems)

Analyzed security policies, e.g. for privacy regulations.

T··Systems·
Allianz
Deutsche Bank
HypoVereinsbank
CEPS™
BMW Group
Münchener Rück
Munich Re Group
Bundesministerium für Bildung und Forschung
Bundesministerium für Wirtschaft und Technologie
$O_2$
infineon

# Conclusion

Seemingly first attempt at formally based security verification for crypto-based Java legacy implementations.

Use interface specification to make verification of large-scale implementations feasible.

Goals: Emphasis on automation, reach efficiency using abstraction tailored to verification problem.

Experiences so far encouraging.

Still many challenges to address – collaboration always welcome !

# Questions ?

More information (papers, slides, tool etc.):

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