Security protocols, properties, and their monitoring
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Model-based Security Engineering

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

- Tool-supported, theoretically sound, efficient automated security design & analysis.
Insert recurring security requirements, adversary scenarios, security mechanisms as predefined markers.

Use associated logical constraints to verify specifications using model checkers and ATPs based on formal semantics.

Ensures that UML specification enforces the relevant security requirements wrt Dolev-Yao type adversaries.  

[FASE01, UML02, FOSAD05, ICSE05]
Secure System Lifecycle

Model-based Security Engineering

**Design:** Encapsulate prudent security engineering rules.

**Analysis:** Formally based, automated, efficient tools.

Note: emphasis on high-level requirements.
Example: Crypto-based Distributed System

Adversary knowledge: \( k^{-1}, y, x \) \( \{z\}_k, z \)

Attacker may …
• control system parts,
• know data in advance,
• intercept messages,
• delete messages,
• inject messages.

(cf. [Dolev, Yao 1982])
Security Analysis in First-order Logic

Approximate adversary knowledge set from above:

Predicate \(\text{knows}(E)\) 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 \(\text{knows}(s)\) from model-generated formulas using automatic theorem prover. [ICSE05]
**Example:**
Translation to Logic

\[
\text{knows}(N) \land \text{knows}(K_C) \land \text{knows}(Sign_{K_C^{-1}}(C::K_C)) \\
\land \forall \text{init}_1, \text{init}_2, \text{init}_3. [\text{knows}(\text{init}_1) \land \text{knows}(\text{init}_2) \land \text{knows}(\text{init}_3) \land \text{snd}(\text{Ext}_{\text{init}_2}(\text{init}_3)) = \text{init}_2 \\
\Rightarrow \text{knows}(\{\text{Sign}_{K_S^{-1}}(\ldots)\}) \land [\text{knows}(\text{Sign}\ldots)] \\
\land \forall \text{resp}_1, \text{resp}_2. [... \Rightarrow ...]]
\]
Analysis

Check whether can derive \textit{knows(s)} e.g. using e-Setheo.

Surprise: Yes!

\rightarrow Protocol does not preserve secrecy of \textit{s}.

Why? Use Prolog-based attack generator.
Static Model Verification

Static model verification works well if sufficient to check the model of a system (and not the physical asset).

• System model captures all relevant aspects about a system.
  – No problem, if code is generated from it, but in practice, this is not always the case.

• Assumptions about influences from a system's operational environment are reflected adequately.
  – Influences from the physical environment potentially infinitely many, e.g., think of a control system for a combustion engine.
Security Analysis: Model or Code?

Model:
+ earlier (less expensive to fix flaws)
+ more abstract $\Rightarrow$ more efficient
- more abstract $\Rightarrow$ may miss attacks
- programmers may introduce security flaws
- even code generators, if not formally verified

Code:
+ „the real thing“ (which is executed)

$\Rightarrow$ Do both!

Note: Almost no existing work (wrt crypto protocols).
Code Analysis vs. Model Analysis

Options:

• generate code from models
  → currently not available in general

• generate models from code
  → currently not available (for real-life software and right level of abstraction)

→ create models and code manually and verify code against models

→ This talk: run-time verification.
Run-time Verification

• Checking the actual behaviour of a system in its operational environment can be important.

• Need to validate the hidden assumptions that need to be made to reach a sufficient level for abstraction to enable automated static verification of non-trivial systems.

→ Do run-time verification / monitoring.
Verify Code against Models

Assumption: Have textual specification.

Then:

• construct interface spec from textual spec
• analyze interface spec for security
• verify that software satisfies interface spec (using run-time verification)
Model vs. Implementation

Elements of connections

Josie - using RSA & Server authentication

Implement-ation

Send and received data

Backtrace assignments

"meaning"

"meaning"

Defined during model creation

Find

Has

Implements?
Dynamic verification technique on the actual system.

Essentially a symbiosis of model-checking and testing.

“Lazy model-checking”: only check the system traces which are executed, when they are executed.
Formal underpinnings

- System (safety) property, \( \varphi \) specified in terms of linear time temporal logic [Pnu77]:
  \[
  \varphi ::= true \mid p \mid \neg p \mid \varphi \odot \varphi \mid \varphi U \varphi \mid X \varphi \quad (p \in AP)
  \]

- Continuous interpretation of \( \varphi \) over sequence of system events (behaviours), \( u \in (2^{AP})^* \)

- **Automatic monitor generation:** “Inspired” by translation of LTL to Büchi-automata

  \[
  \varphi \rightarrow BA_\varphi \text{ s.t. } L(BA_\varphi) = L(\varphi)
  \]
Semantics

\[ w, i \models true \]
\[ w, i \models \neg \varphi \iff w, i \not\models \varphi \]
\[ w, i \models p \in AP \iff p \in w(i) \]
\[ w, i \models \varphi_1 \lor \varphi_2 \iff w, i \models \varphi_1 \lor w, i \models \varphi_2 \]
\[ w, i \models \varphi_1 U \varphi_2 \iff \exists k \geq i. w, k \models \varphi_2 \wedge \]
\[ \forall i \leq l < k. w, l \models \varphi_1 \]
\[ w, i \models X\varphi \iff w, i + 1 \models \varphi \]

*We write* \( w \models \varphi, \) *if and only if* \( w, 0 \models \varphi, \) *and use* \( w(i) \) *to denote the* \( i \) *th element in* \( w. \)*

*Write* \( F \) *phi for* \( true \) \( U \) *phi ("eventually phi"); \( G \) *phi for not* \( F \) *not phi ("globally phi"); \( \varphi_1 \) \( W \) \( \varphi_2 \) *for* \( G \) *\( \varphi_1 \) or (\( \varphi_1 \) \( U \) \( \varphi_2 \)) (weak-until)
Monitoring-friendly LTL semantics

3-valued semantics:

\[ [u \models \varphi] = \begin{cases} 
\top & \text{if } \forall \sigma \in \Sigma^\omega : u \sigma \models \varphi \\
\bot & \text{if } \forall \sigma \in \Sigma^\omega : u \sigma \not\models \varphi \\
? & \text{otherwise}
\end{cases} \]

Gives finite-state machines for detecting *minimal* bad prefixes:

![Finite-state machine diagram](image)

*Predictiveness*

- *true*
- *false*
- *inconclusive*
Example: Interface spec of SSL

1) Identify program points:
   value (r), receive (p), guard (g), send (q)

II) Check guards enforced
<table>
<thead>
<tr>
<th>Parameter der kryptographischen ClientHello Nachricht</th>
<th>Effektiv übertragene Daten der ClientHello Nachricht der Jessie Implementierung</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>type.getValue()</td>
</tr>
<tr>
<td>Pver</td>
<td>major</td>
</tr>
<tr>
<td></td>
<td>minor</td>
</tr>
<tr>
<td></td>
<td>((gmtUnixTime &gt;&gt;&gt; 10) &amp; 0xFF)</td>
</tr>
<tr>
<td></td>
<td>((gmtUnixTime &gt;&gt;&gt; 8) &amp; 0xFF)</td>
</tr>
<tr>
<td></td>
<td>(gmtUnixTime &amp; 0xFF)</td>
</tr>
<tr>
<td>r_c</td>
<td>randomBytes</td>
</tr>
<tr>
<td></td>
<td>sessionId.length</td>
</tr>
<tr>
<td></td>
<td>sessionId</td>
</tr>
<tr>
<td></td>
<td>((suites.size() &lt;&lt; 1) &gt;&gt;&gt; 8 &amp; 0xFF)</td>
</tr>
<tr>
<td></td>
<td>((suites.size() &lt;&lt; 1) &amp; 0xFF)</td>
</tr>
<tr>
<td>LCip</td>
<td>suites_1</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>suites_N</td>
</tr>
<tr>
<td>LKomp</td>
<td>comp.size()</td>
</tr>
<tr>
<td></td>
<td>comp_1</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>comp_N</td>
</tr>
</tbody>
</table>
public void write(OutputStream out) throws IOException {
    ...
    out.write(randomBytes);
    ...
}

Identify: randomBytes

(in message ClientHello)

2nd parameter of ClientHello constructor

ClientHello(..., Random random, )
{
    ...
    this.random = random;
    ...
}

2nd parameter of ClientHello constructor called by ClientHello.write()

public void write(OutputStream out) throws IOException {
    ...
    random.write(out);
    ...
}

via Handshake.write()
initialized in SSLSocket.doClientHandshake()

ClientHello clientHello = new ClientHello(..., clientRandom,...);

initialization of the used Random object

Random clientRandom =
new Random(..., session.random.generateSeed(28));

class SecureRandom (specified in: FIPS 140-2, RFC 1750) of package java.security

Function: generateSeed
Sending Messages

Automate this using patterns

SSLSocket.doClientHandshake()
Checking Guards

Guard $g$ enforced by code? 
Here: Generate runtime-verification checks for $g$ at $q$ from diagram. 

[Alternatives: Testing against checks (symbolic crypto for inequalities); Automated formal local verification: conditionals between $p$ and $q$ logically imply $g$ (using ATP for FOL).]
public void checkServerTrusted(X509Certificate[] chain, String authType) throws CertificateException {
    ... checkTrusted(chain, authType); ...
}

calls checkTrusted()

Guard:
checkServerTrusted()
msg = Handshake.read(din, certType);

session.trustManager.checkServerTrusted(peerCerts, suite.getAuthType());

msg = new Handshake(Handshake.Type.CLIENT_KEY_EXCHANGE, ckex);
msg.write(dout, version);

only possible way without throwing exception
Client will not send out `ClientKeyExchange` message until has received `Certificate` message, and validity check is positive. If that is the case, client will send out `ClientKeyExchange` message eventually.

Figure 1: FSM $\neg \text{ClientKeyExchange}_S \cup \text{Certificate}_R$. 

not safety but co-safety
Server Finished

Server will not send Finished message before has checked that MD5 received in Client`s Finished message is equal to MD5 created by server, and correspondingly for SHA hash. Will send it out eventually after that has been established.

\[ \varphi_2 = \neg \text{Finished}_S \bigwedge (MD5(\text{Finished}_R) = MD5(\text{Finished}_S)) \land (F(MD5(\text{Finished}_R) = MD5(\text{Finished}_S)) \Rightarrow F\text{Finished}_S) \]

(and similar for SHA).

neither safety nor co-safety
Client Transport Data

Client will not send any transport data before has checked that MD5 hash received in Server`s **Finished** message is equal to MD5 created by Client (and correspondingly for SHA hash).

\[
\varphi_3 = \neg DataW((MD5(Finished_R) = MD5(Finished_S)),
\]

not co-safety but safety
Conclusion

Seemingly first approach to run-time security verification for crypto-based Java implementations. Integrated with static verification of UMLsec models. Exceeds previous approaches such as Fred Schneider’s security automata in expressivity. Run-time verification approach used optimally efficient (regarding space complexity).
Questions?

More information (papers, slides, tool etc.):
http://www.umlsec.org

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