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Security Analysis of Software Design

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Master Course “Secure Software Engineering”
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Learning objectives

- What are architectural weaknesses?
  - CAWE

Reading material
Mehdi Mirakhorli, Common Architecture Weakness Enumeration (CAWE),
http://blog.ieeesoftware.org/2016/04/common-architecture-weakness.html

- How to find architectural weaknesses with model-based security analysis?
  - Manual inspection vs automated checking (UMLsec)

Reading material
Jan Jürjens, *Model-Based Security Engineering with UML*,
Chapter 4 of the book "Secure Systems Development with UML"
Link: https://link.springer.com/chapter/10.1007/3-540-26494-9_4

Goals of model-based security analysis

- Discover security/privacy issues early on, even before developing the code (forward engineering case)

- Certification of a system (also existing one)
  - Evidence that risks are identified
  - Evidence that ‘reasonable’ security mechanisms are in place

Model Based Security Analysis

Why security analysis at the architecture level?

For the early identification of the security design flaws

A different type of issues (than, e.g., implementation vulnerabilities)

Are security tests/validation on the implementation not sufficient?

Quite evident with the no. of attacks!

Late detection and fixing security flaws causes loss of time, money and reputation of the organization

Architectural Flaws

- **Flaws of Omission.** Such design flaws result from ignoring a security requirement or potential threats.
- **Flaws of Commission.** Such design flaws refer to the design decisions which were made and could lead to undesirable consequences.
- **Flaws of Realization.** The design decision is correct but the implementation of that suffers from a coding mistake. Code vulnerabilities TERRITORY

- Common Architecture Weakness Enumeration (CAWE)
- *By Mehdi Mirakhorli*
- http://blog.ieeesoftware.org/2016/04/common-architecture-weakness.html

An example

Listing 1 An example of an incorrect implementation of the tactic "Authenticate Actors" in a Web application written in PHP resulting in an authentication-bypass.

```
1   $auth = $_COOKIES['authenticated'];
2   if (!$auth) {
3       if (authenticate($_POST['username'], $_POST['password'])) {
4           // save the cookie to be sent out in future responses
5           setcookie('authenticated', '1', time()+60*60*2);
6       } else {
7           showLoginScreen(); // request user to login
8           die('\n'); // kill the process
9       }
10  }
11  performPrivilegedAction();
```

Architectural weaknesses

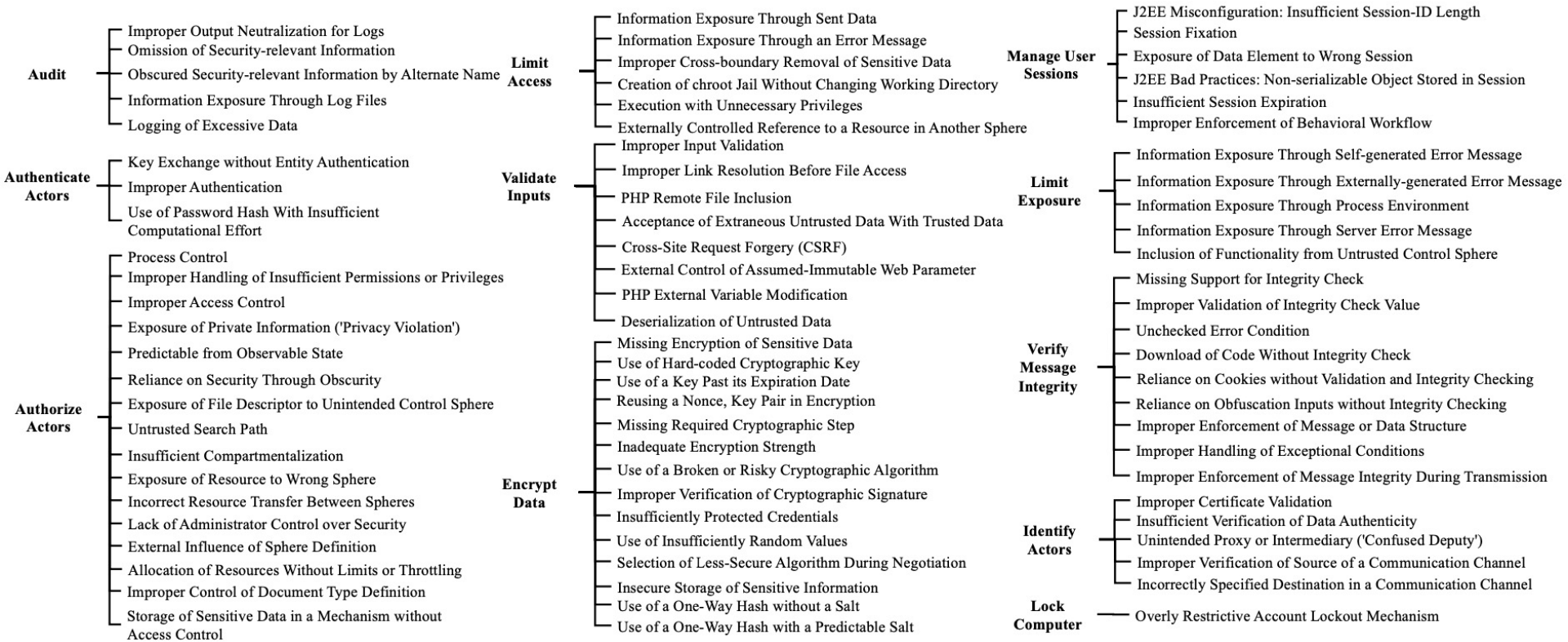
Top 10 Software Security Design Flaws

1. Earn or Give, but Never Assume, Trust
2. Use an Authentication Mechanism that Cannot be Bypassed or Tampered With
3. Authorize after You Authenticate
4. Strictly Separate Data and Control Instructions, and Never Process Control Instructions Received from Untrusted Sources
5. Define an Approach that Ensures all Data are Explicitly Validated
6. Use Cryptography Correctly
7. Identify Sensitive Data and How They Should Be Handled
8. Always Consider the Users
9. Understand How Integrating External Components Changes Your Attack Surface
10. Be Flexible When Considering Future Changes to Objects and Actors

CAWE

Common Architectural Weakness Enumeration

Accepted as a “view” in CWE



Model-based security analysis

- Inspection guidelines
- Algorithmically
  (e.g., model checking, pattern matching, etc.)
- Threat and risk analysis → Later in this course ;)

Types of model-based security analysis

- Inspection guideleines
  (performed manually, possibly tool assisted)

Design Flaw 1: Missing authentication

Description This refers to the absence of an authentication mechanism in the system. Apart from external entities, like users or other systems the system may interact with, authentication may be necessary within the system between processes/components/datastores that are located in different trust boundaries.

Detection

- Consider the external entities (users/subsystems) that interact with the system and which assets of the system they can access.
- Determine the processes that interact with high-value assets in the system.
- For each interaction examine:
  - If it is an entity: Does the entity go through an authentication point in order to access the asset?
  - If it is a process: Is the identity of a process accessing datastores or processes in a different part of the system (trust boundaries – requires different privilege levels) verified?

K. Tuma et al., **Automating the Early Detection of Security Design Flaws**, MODELS 2020

- Benchmark is a ‘trendier’ term
  (see CIS – Center for Internet Security)
  - Also more focus on tool support for the rules

Manual vs Automated Model Analysis

Accessing the software design/software architecture for detection of flaws

Analysis	Advantages	Disadvantages
Manual	• Interpretation of improper representation of models • Fewer false positives	• Time consuming • Requires expertise • Completeness ?
Automated	• Faster • Re-executed if model changes	• Specific Model with precise notation/formalism are required • Additional info to be added to models based on rules and requirements

UMLSec

Unified Modeling Language (UML)

UML: Industry standard object oriented modeling technique
Relatively precisely defined
Widely adopted and accepted

UML Diagrams

Rich set of diagrams, covering a spectrum of abstractions (more/less detailed descriptions)

Visual representation of the architecture and detailed design of complex software systems

UML Diagrams	
Structural Diagrams	Behavioral Diagrams
Class Diagram	Use Case Diagram
Component Diagram	Activity Diagram
Deployment Diagram	State Machine Diagram
Object Diagram	Sequence Diagram
Package Diagram	Communication Diagram
Profile Diagram	Interaction Overview Diagram
Composite Structure Diagram	Timing Diagram

UMLsec – Phylosophy

- Annotate design diagrams with various recurring security requirements (secrecy, integrity, authenticity…) and security assumptions
- Annotations as
  - Stereotypes
  - Tags
- Goal
  - Documentation / keep track of info
  - Formal semantics → tool-supported analysis

UMLSec Extension Mechanisms

UML profile collects the relevant definitions of stereotypes, tagged values, and constraints

Stereotypes Define new sub-types of modelling elements, hence extending the UML metamodel. Stereotype definition can include zero or more tags

Example: <<guarded>> can only be used on Objects

Tagged values: Name-value pair that add properties to model elements. Can be used in the context of a stereotypes that defines them

Example: {guard = obj} identifies the guard object

Foo Boolean values, {tag} means {tag = true}

Constraints Define the formal semantics of a model element (e.g., written in first-order logic). That is, the desired security property.

Example: "guarded objects only accessible via guard object"

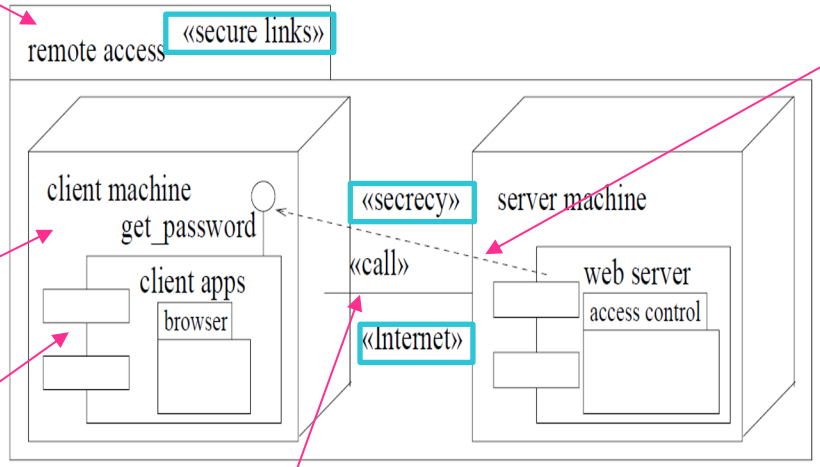
Example

Stereotype	Base Class	Tags	Constraints	Description
Internet	link			Internet connection
encrypted	link			encrypted connection
LAN	link,node			LAN connection
wire	link			wire
secure links	subsystem		dependency security matched by links	enforces secure communication links
secrecy	dependency			assumes secrecy
integrity	dependency			assumes integrity
high	dependency			high sensitivity

Subsystem (think of package)
Integrate the information between the different kinds of diagrams and between different parts of the system specification

Deployment diagram with

Security annotations



Dependency (between components)

Node

Component

Link (between nodes)

UMLSec: usage scenarios
(from more abstract to more concrete)

Usecase diagrams

Seen before

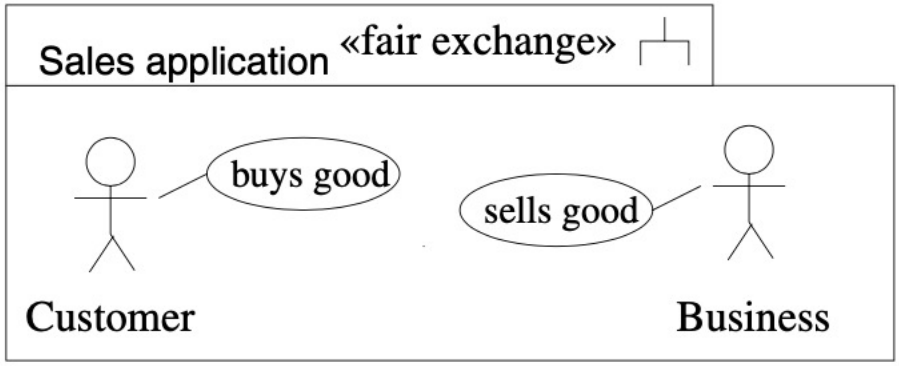


Fig. 2.1. Use case diagram for business application

In UMLsec: Capture security requirements

Activity diagrams

Specify the control flow between several components within the system, usually at a higher degree of abstraction than statecharts and sequence diagrams. They can be used to put objects or components in the context of overall system behaviour or to explain use cases in more detail.

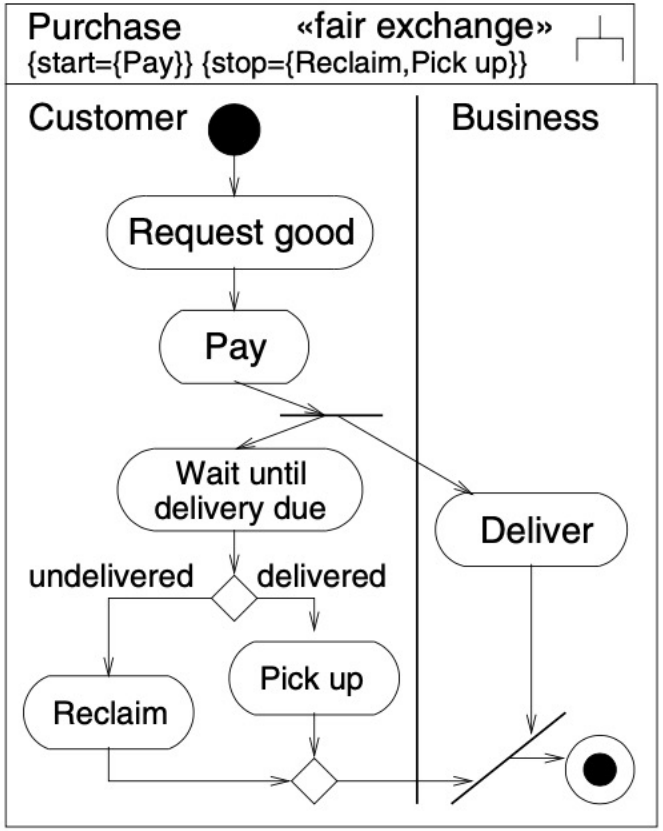


Fig. 2.2. Purchase activity diagram

In UMLsec: Define secure business processes

Deployment diagrams

Describe the physical layer on which the system is to be implemented.

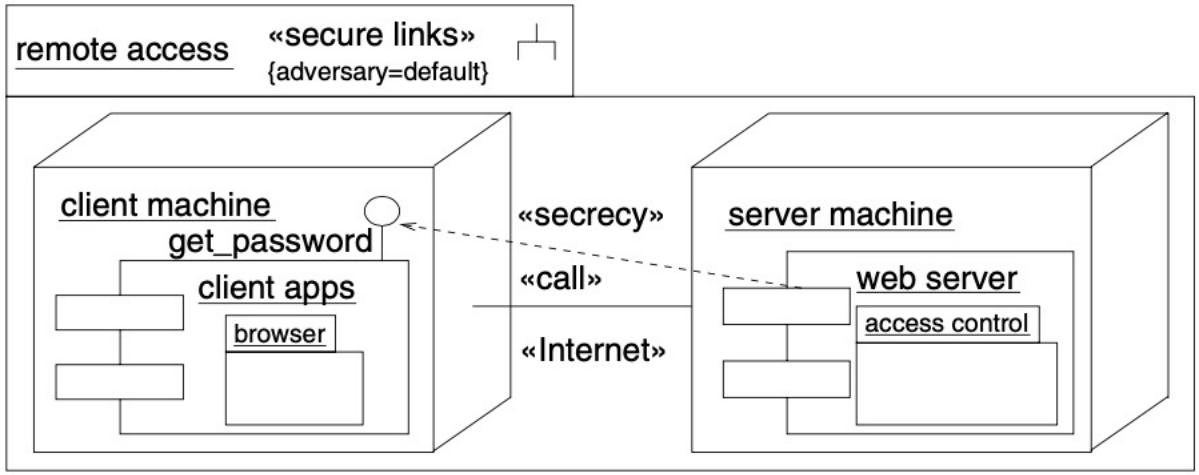


Fig. 2.3. Example *secure links* usage

In UMLsec: Check physical security

Sequence diagrams

Describe interaction between objects arranged in time sequence and also sequence of the messages exchanged.

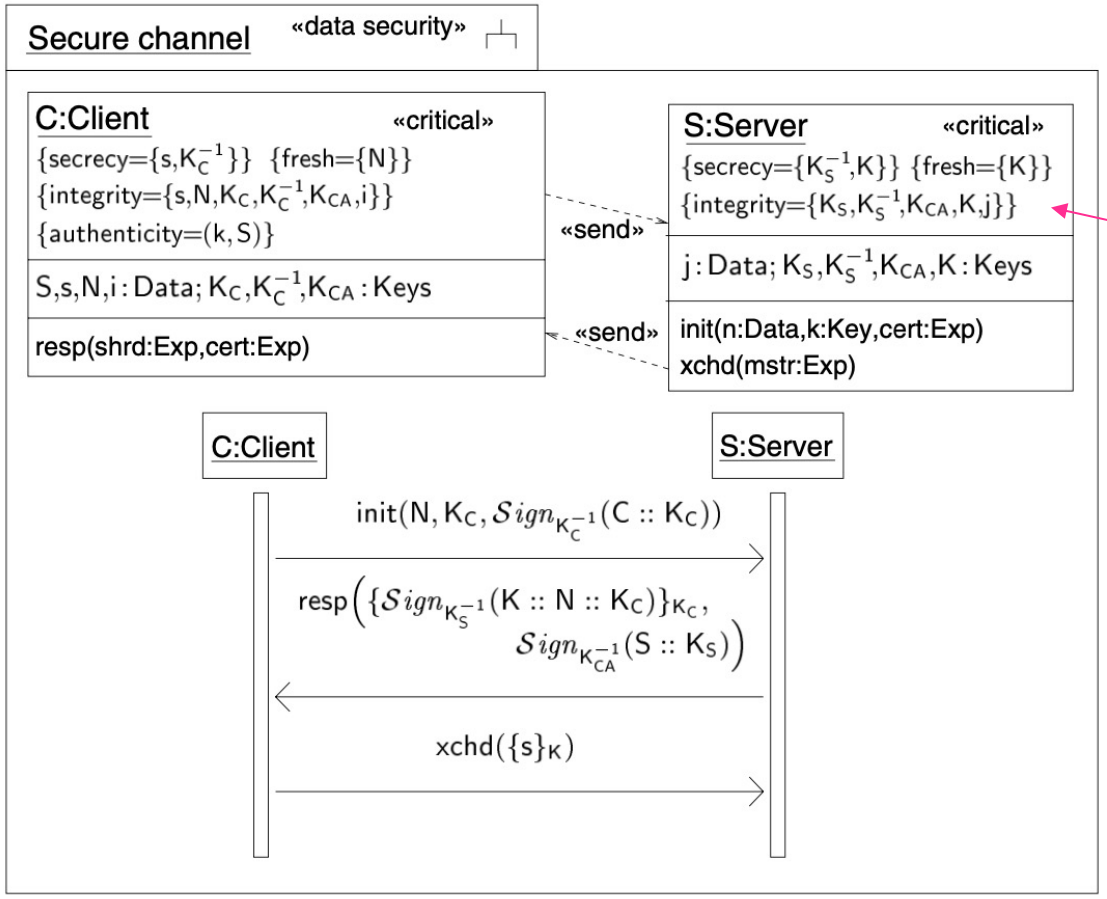


Fig. 2.4. Key exchange protocol

Class diagrams

Define the static class structure of the system: classes with attributes, operations, and signals and relationships between classes. On the instance level, the corresponding diagrams are called ***object*** *diagrams.*

In UMLsec: Define security critical interactions

Statechart diagrams

Give the dynamic behaviour of an individual object or component: events may cause a change in state or an execution of actions.

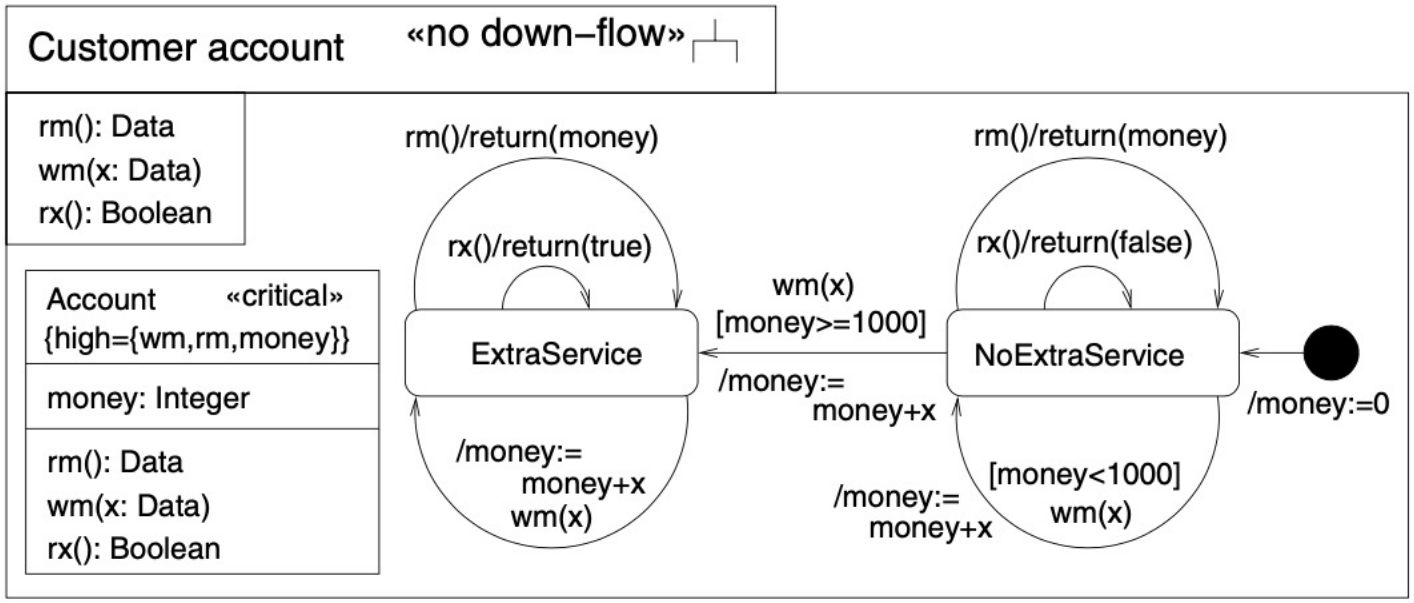


Fig. 2.5. Customer account data object

In UMLsec: Information flow analysis

UMLsec profile at a glance

Stereotype	Base Class	Tags	Constraints	Description
fair exchange	subsystem	start, stop, adversary	after start eventually reach stop	enforce fair exchange
provable	subsystem	action, cert, adversary	action is non-deniable	non-repudiation requirement
rbac	subsystem	protected, role, right	only permitted activities executed	enforces role-based access control
Internet	link			Internet connection
encrypted	link			encrypted connection
LAN	link, node			LAN connection
wire	link			wire
smart card	node			smart card node
POS device	node			POS device
issuer node	node			issuer node
secrecy	dependency			assumes secrecy
integrity	dependency			assumes integrity
high	dependency			high sensitivity
critical	object, subsystem	secrecy, integrity, authenticity, high, fresh		critical object
secure links	subsystem	adversary	dependency security matched by links	enforces secure communication links
secure dependency	subsystem		«call», «send» respect data security	structural interaction data security
data security	subsystem	adversary, integ., auth.	provides secrecy, integrity, authenticity, freshness	basic data security requirements
no down-flow	subsystem		prevents down-flow	information flow condition
no up-flow	subsystem		prevents up-flow	information flow condition
guarded access	subsystem		guarded objects accessed through guards	access control using guard objects
guarded	object	guard		guarded object

Stereotypes 1/3

Internet, encrypted LAN: Denote communication links- Stereotypes on links in deployment diagrams denote the corresponding requirements on communication links nodes. Each link or node carries at most one of these stereotypes.

Secure Dependency

This stereotype, used to label subsystems containing object diagrams or static structure diagrams, ensures <<call>> or <<send>> dependencies respect the security requirements on the data that may be communicated along them, as given by the tags secrecy, integrity and high of the stereotype <<critical>>

Secrecy, integrity, high

Stereotypes denote dependencies in static structure or component diagrams that provide security requirement for the data that is sent as arguments or return values of operations or signals.

Stereotypes 2/3

Secrecy

<<call>> or <<send>> dependencies in object or component diagrams stereotyped <<secrecy>> provide security requirement for the data that is sent as arguments or return values of operations or signals

Both are used in the constraint of the stereotype <<secure links>>

Critical

This stereotype labels objects or subsystem instances containing data that is critical in some way, which is specified in more detail using the tags secrecy, integrity, fresh and high.

No down flow

This stereotype of subsystems enforces secure information flow by making use of the associated tag high. According to the <<no-down flow>> constraint, the stereotyped subsystem prevents down-flow wrt messages and their return messages specified as high

Stereotypes 3/3

Fair exchange

Tags *start* and *stop* whenever a start state in the activity diagram is reached, then eventually corresponding stop state will be reached.

Provable

Tags *action* and *cert* whenever a start state in the activity diagram is reached, then eventually corresponding stop state will be reached.

Guarded Access

Each object in the subsystem that is <<guarded>> can only be accessed through the objects specified by the tag guard attached
to <<guarded>> object.

Guarded

Labels objects (in particular in the scope of the stereotype <<guarded access>> above) that are supposed to be guarded. It has a tagged value guard which defines the name of the corresponding guard object.

Only for your info

Summary of UMLsec tags

Tag	Stereotype	Type	Multip.	Description
start	fair exchange	state	*	start states
stop	fair exchange	state	*	stop states
adversary	fair exchange	adversary model	1	adversary type
action	provable	state	*	provable action
cert	provable	expression	*	certificate
adversary	provable	adversary model	*	adversary type
protected	rbac	state	*	protected resources
role	rbac	(actor, role)	*	assign role to actor
right	rbac	(role, right)	*	assign right to role
secrecy	critical	data	*	secrecy of data
integrity	critical	(variable, expression)	*	integrity of data
authenticity	critical	(data, origin)	*	authenticity of data
high	critical	message	*	high-level message
fresh	critical	data	*	fresh data
adversary	secure links	adversary model	1	adversary type
adversary	data security	adversary model	1	adversary type
integrity	data security	(variable, expression)	*	integrity of data
authenticity	data security	(data, origin)	*	authenticity of data
guard	guarded	object name	1	guard object

Key security requirements

Stereotype	Base Class	Tags	Constraints	Description
fair exchange	subsystem	start, stop, adversary	after start eventually reach stop	enforce fair exchange
provable	subsystem		ble	non-repudiation requirement
rbac	subsystem		executed	enforces role-based access control
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Non-repudiation of actions

Coarse-grain access control

Confidentiality & integrity of communications

Information flow properties

Architectural access control

Study at home

UMLsec: Supported Security Requirements

Fair Exchange- This requirement postulates that the trade is performed in a way that prevents both parties from cheating

Non-Repudiation- An action cannot subsequently be denied successfully. That is, the action is provable, usually wrt. some trusted third party

Secure Logging- The auditing data is at each point during the transaction of the system consistent with the actual state of the transaction (to avoid the possibility of fraud by interrupting the transaction)

Message Authenticity or Data origin Authenticity- Allows to identify the original source of data in the past

Entity Authenticity- Allows to identify active participation of a participant in a particular protocol at that time

Guarded Access- Access control ensures that only legitimate parties have access to a security-relevant part of the system. Access control can be enforced by guards.

UMLsec: Supported Security Requirements

Freshness- A message is fresh if it is created under the current execution round of the system under consideration and cannot replay an older message by the attacker

Secure Information Flow- This requirement is to ensure there is no indirect leakage of sensitive information from a trusted to an untrusted part. Trusted parts of a system are often marked as high, untrusted parts as low

Secrecy and Integrity- These are main data security requirements. A subsystem *S* preserves the secrecy (a.k.a.confidentiality) of an expression *E* from adversary *A* if *E* never appears in the knowledge set *K* of *A* during execution of *S.* Integrity means that some information can be modified only by legitimate parties.

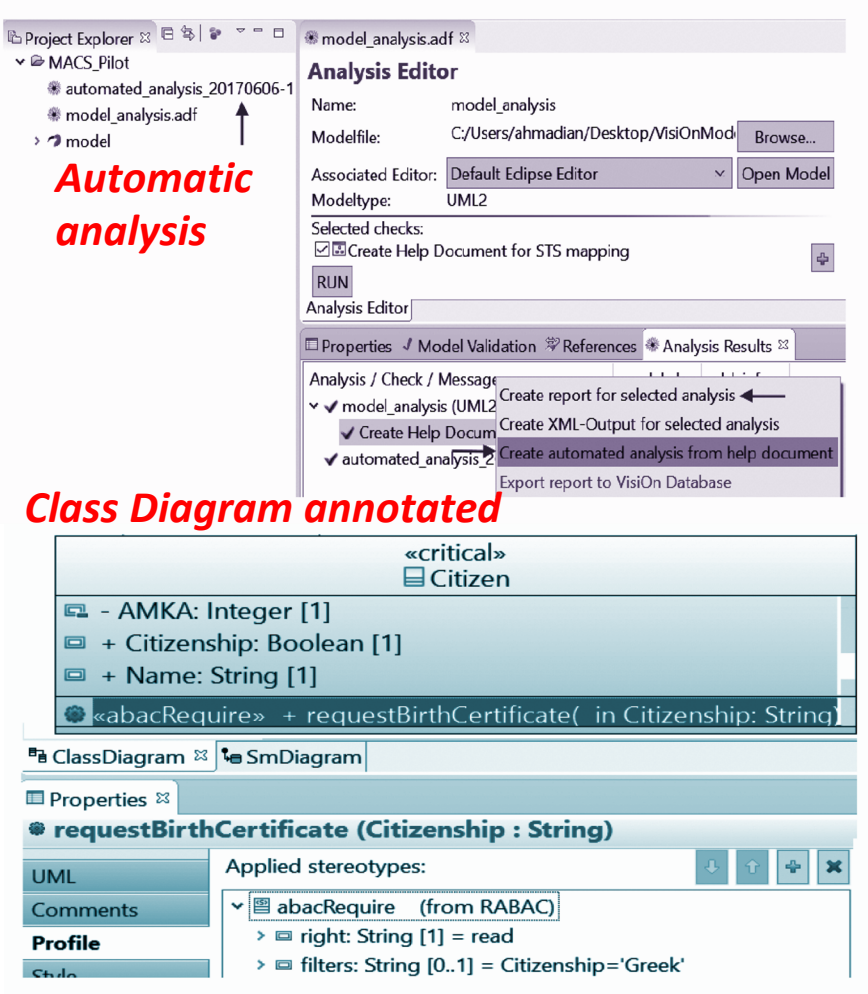
Secure Communication Link- Sensitive communication between different parts of a system needs to be protected. The relevant requirement of a secure communication link is here assumed to provide secrecy and integrity for the data in transit.

UMLSec: model analysis

UML Model Analysis with CARiSMA

- Analyse security requirements based on the information from
  (i) formal semantics
  (ii) adversary behaviour

- UMLsec diagrams are converted to first-order logic formulas (including epistemic constructs)
- Analysis of the diagrams using automated first-order logic theorem provers (e.g., e-SETHEO or SPASS)



More information about CARiSMA:
https://rgse.uni-koblenz.de/carisma/
https://youtu.be/b5zeHig3ARw

Adversary in UMLsec

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Adversary in UMLsec

- Type of adversary can be specified in the UML diagram
- If not specified, capability of default attacker is used

Stereotype	$\text{Threats}_{default}()$
Internet	{delete, read, insert}
encrypted	{delete}
LAN	∅
wire	∅
smart card	∅
POS device	∅
issuer node	∅

Threats from *default* attacker

Stereotype	$\text{Threats}_{insider}()$
Internet	{delete, read, insert}
encrypted	{delete, read, insert}
LAN	{delete, read, insert}
wire	{delete, read, insert}
smart card	∅
POS device	{access}
issuer node	{access}

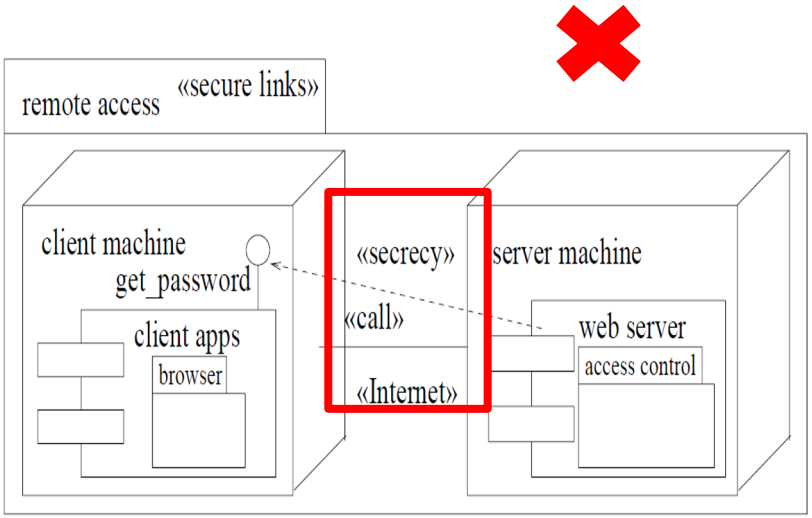
Threats from *insider* attacker

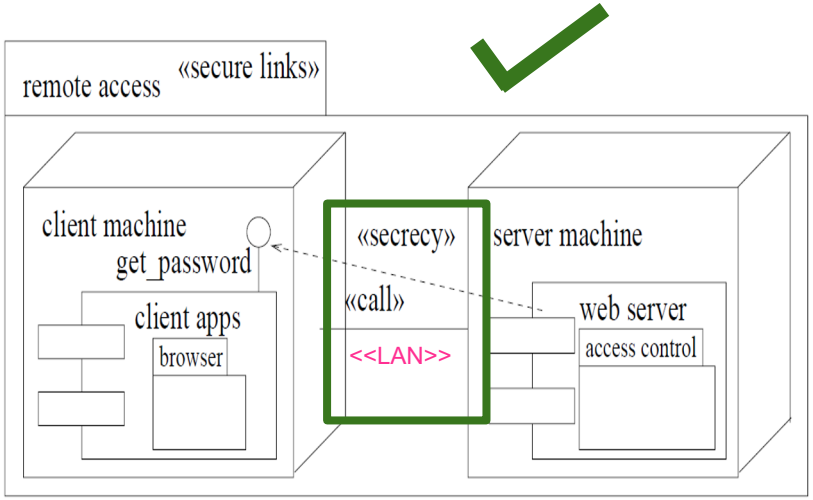
Security analysis for Secure Links

- The model does not meet the secure requirements against the default adversary:
  - In the model, the call dependency is label with the <<secrecy>> constraint
  - The *link* is labeled as **<<Internet>>**
  - The default attacker has *delete*, ***read*** and *insert* capability

Stereotype	$\text{Threats}_{default}()$
Internet	{delete, read, insert}

- An attacker can read messages on an Internet link
- Internet connections do not provide secrecy against attacker
- Constraint is violated



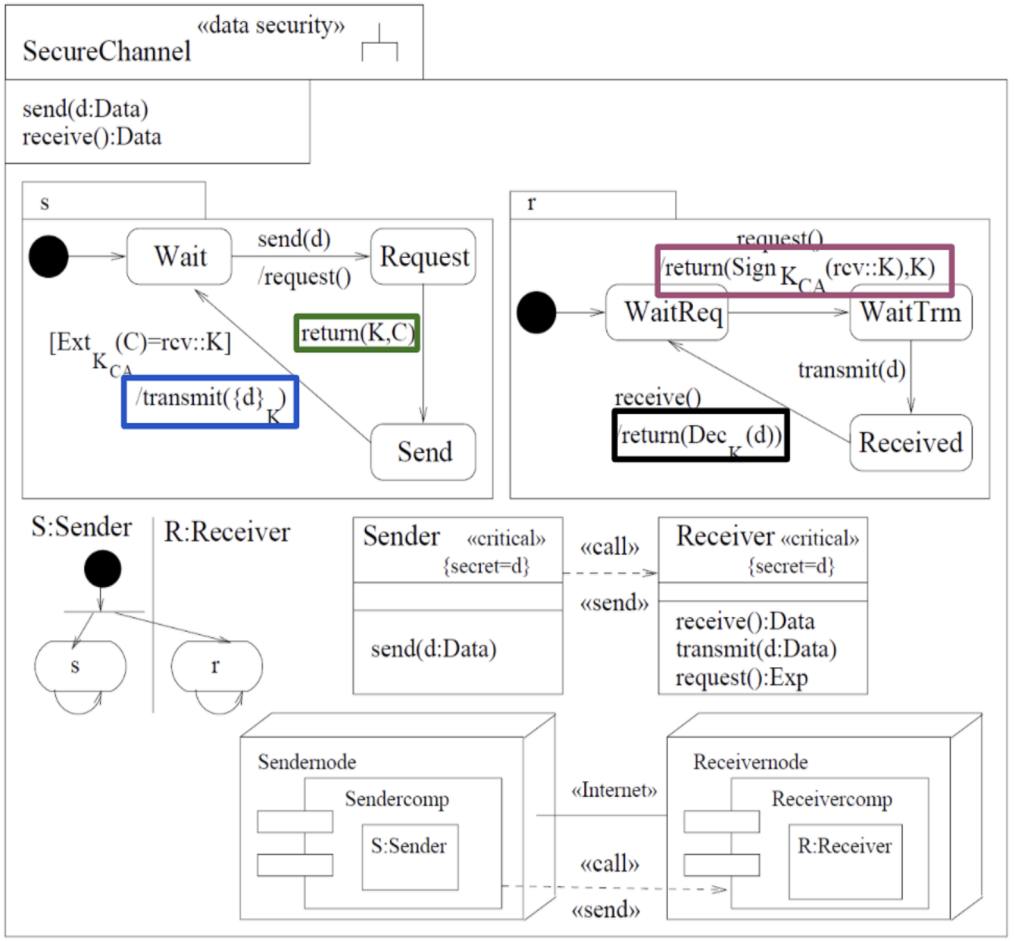


Security analysis for Data Security

Example is a simple security protocol.

1. The sender requests the public key K together with the certificate to certify authenticity of the key from the receiver
2. Receiver sends certificate and the public key to the sender
3. Sender then sends the data back encrypted using K to the receiver
4. Receiver decrypts the ciphertext from the sender using K

The sender and receiver components can interact with each other because of provided *<<call>> and <<send>>*
An internet connection *<<internet>>* is established between the sender and the receiver



Example: Security protocol

Secrecy of d is preserved

Other approaches

Analysis based on Formalized Signatures

- Detailed model describing the system

- System descrition model
  - Component-based model
    (components, interface funcions)
  - Deployment model (components in nodes)
- Security specification model
  - Security objectives (e.g., a component is critical)
  - Security controls
    (e.g., component enforces user authentication)
    (e.g., node in trusted zone)

M. Almorsy, et al., *Automated Software Architecture Security Risk Analysis using Formalized Signatures*, **ICSE 2013**

Analysis based on Formalized Signatures

How does it work

- OCL signatures are *provided*
  (16 in total, more can be added)

- Tool runs the checks on the models
  (model queries and graph navigation)

- Report of results

Attack scenario as OCL signature

```
context System inv Man-in-the-Middle Attack:

self.components->select(C1 |
        C1.DeploymentZone = 'Untrusted' and

        self.components.exists(C2 |
                C2.Channels->exists(Ch |
                        Ch.TargetComponent = C1 and
                        Ch.Encryption = false)

   …
)
```

Model query

Graph navigation

Security metric as OCL signature

```
context System inv AttackSurface:

self.components
        ->select(C1 |
                 C1.DeploymentZone = 'Untrusted‘)
        ->collect(C2 |
                 C2.Functions)
        ->size()
```