Static Program Analysis

Static Analysis for Security

Nanjing University

Tian Tan

2020

Security

Achieving some goals in the presence of adversaries

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Physical World

- Goals
  - Personal safety
  - Property safety
  - …
- Adversaries
  - Thieves
  - Criminals
  - …

Security

Achieving some goals in the presence of adversaries

Physical World

- Goals
  - Personal safety
  - Property safety
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Cyber World

- Goals
  - Dependability
  - Data safety
  - …
- Adversaries
  - Crackers
  - Cyber attackers
  - …

Computer Security

Becomes increasingly important nowadays

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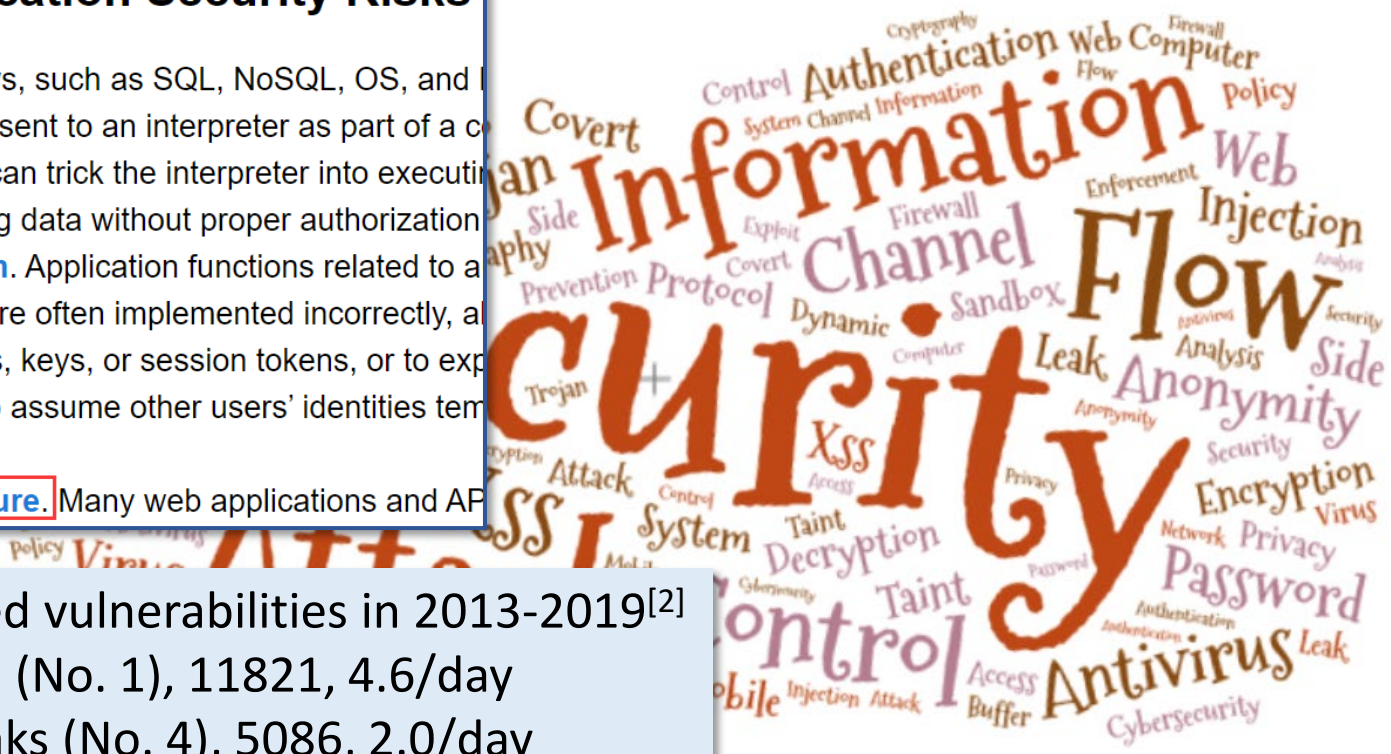
Top 10 Web Application Security Risks [1]

1. **Injection**. Injection flaws, such as SQL, NoSQL, OS, and l when untrusted data is sent to an interpreter as part of a c attacker's hostile data can trick the interpreter into executi commands or accessing data without proper authorization
2. **Broken Authentication**. Application functions related to a session management are often implemented incorrectly, al compromise passwords, keys, or session tokens, or to exp implementation flaws to assume other users' identities tem permanently.
3. **Sensitive Data Exposure**. Many web applications and AP



Causes of exploited vulnerabilities in 2013-2019[2]

- Injection errors (No. 1), 11821, 4.6/day
- Information leaks (No. 4), 5086, 2.0/day

[1] The Open Web Application Security Project, https://owasp.org/
[2] National Vulnerability Database, https://nvd.nist.gov/

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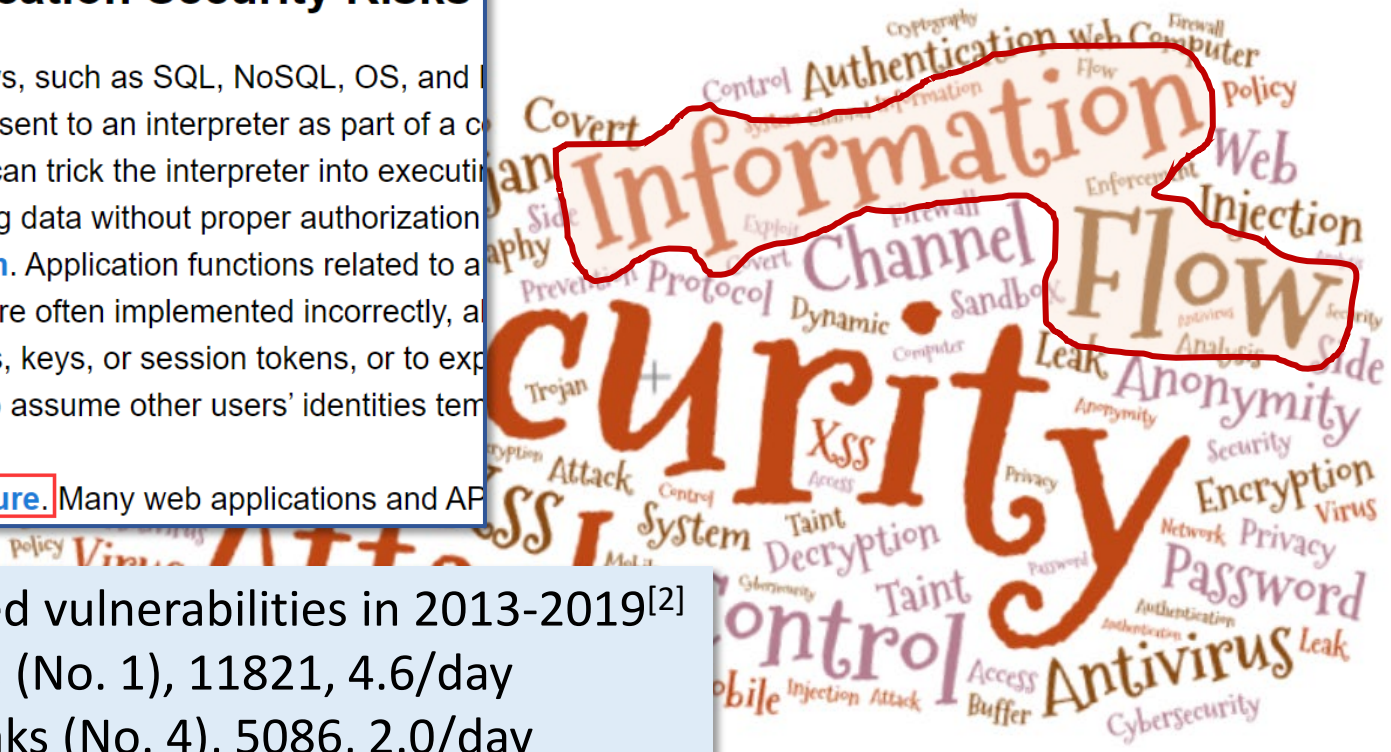

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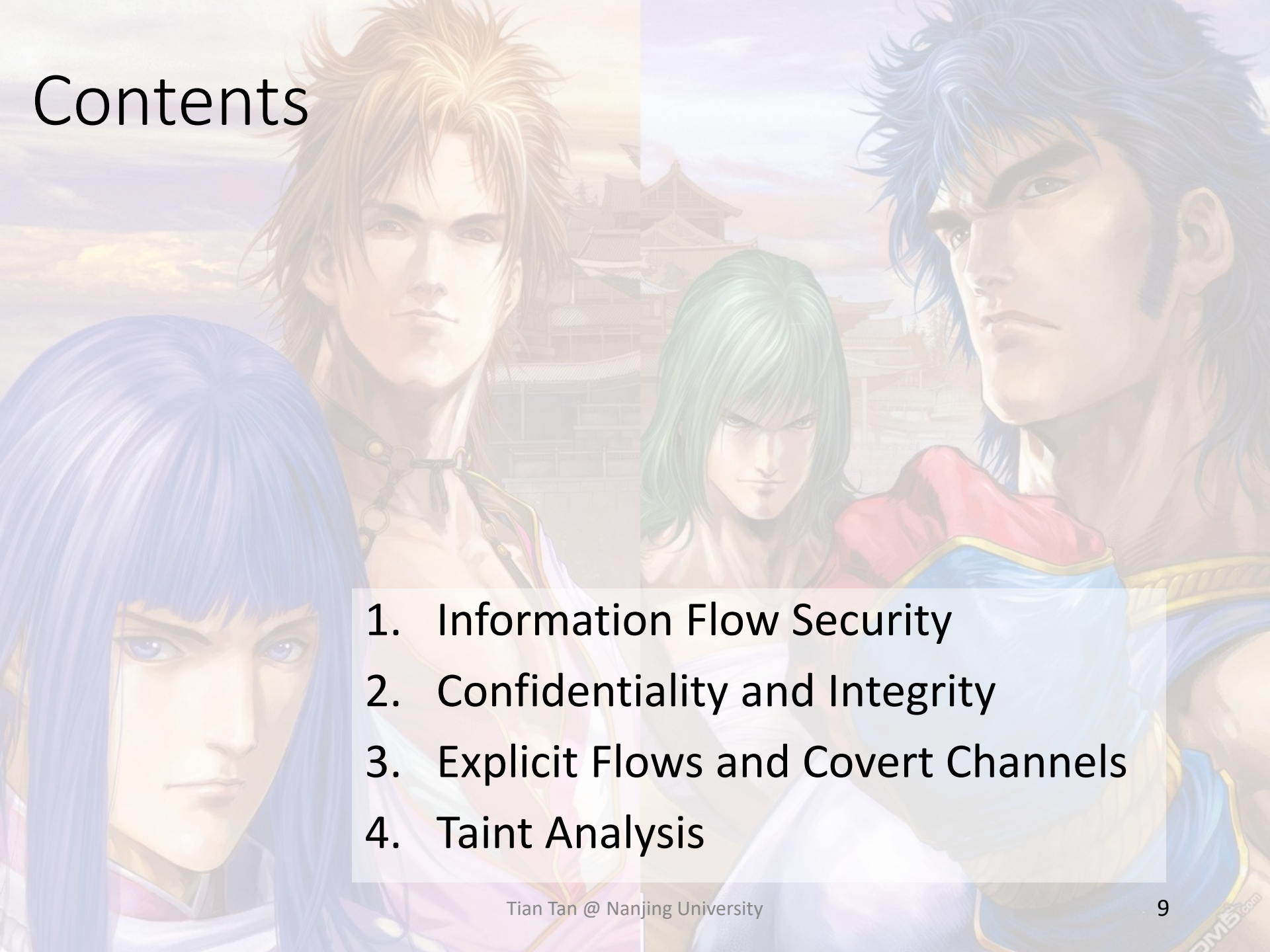
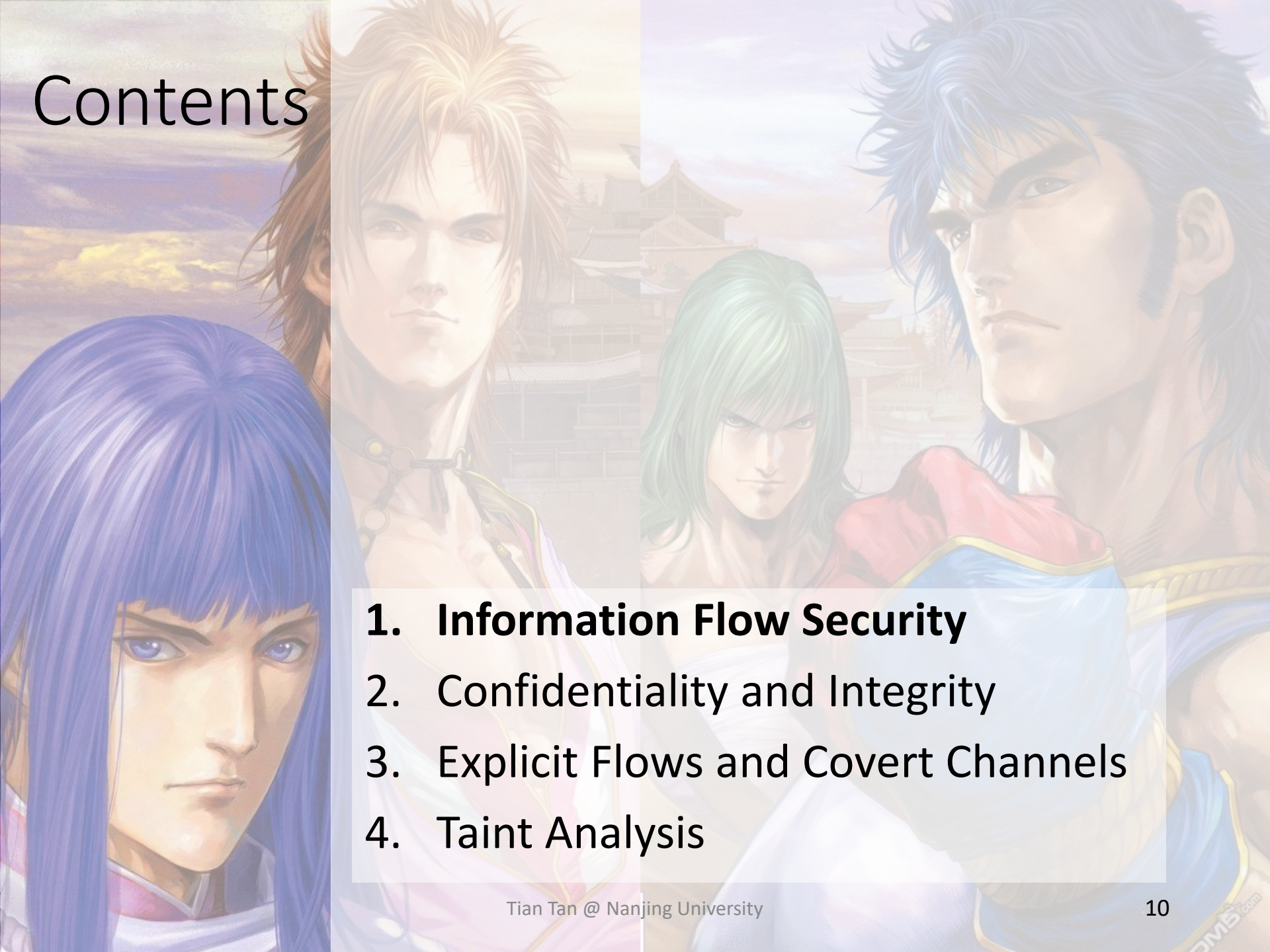


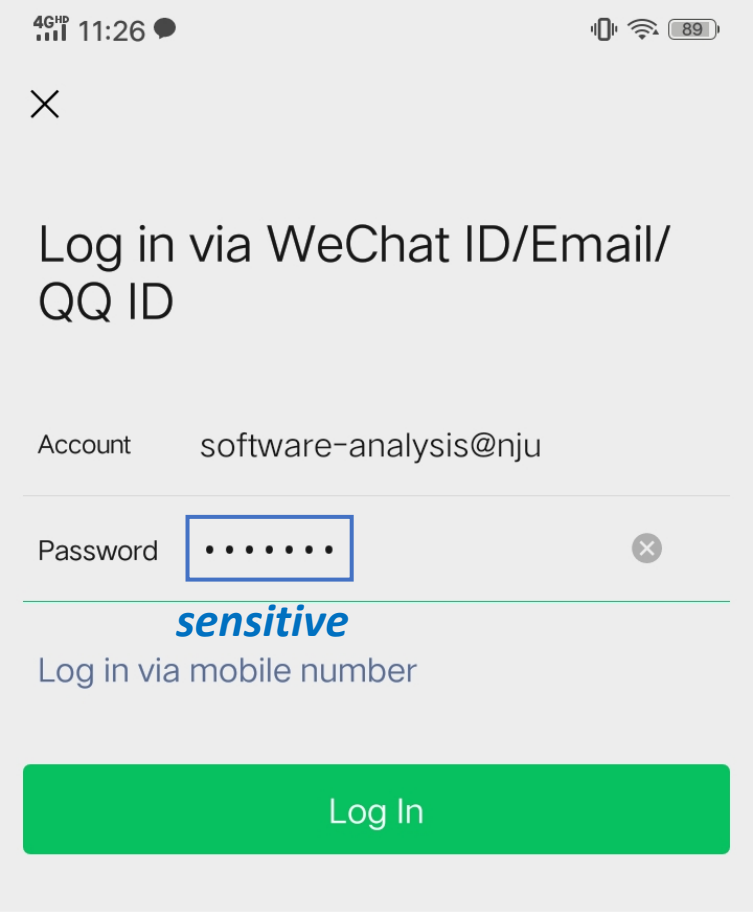
1. Information Flow Security
2. Confidentiality and Integrity
3. Explicit Flows and Covert Channels
4. Taint Analysis

Contents

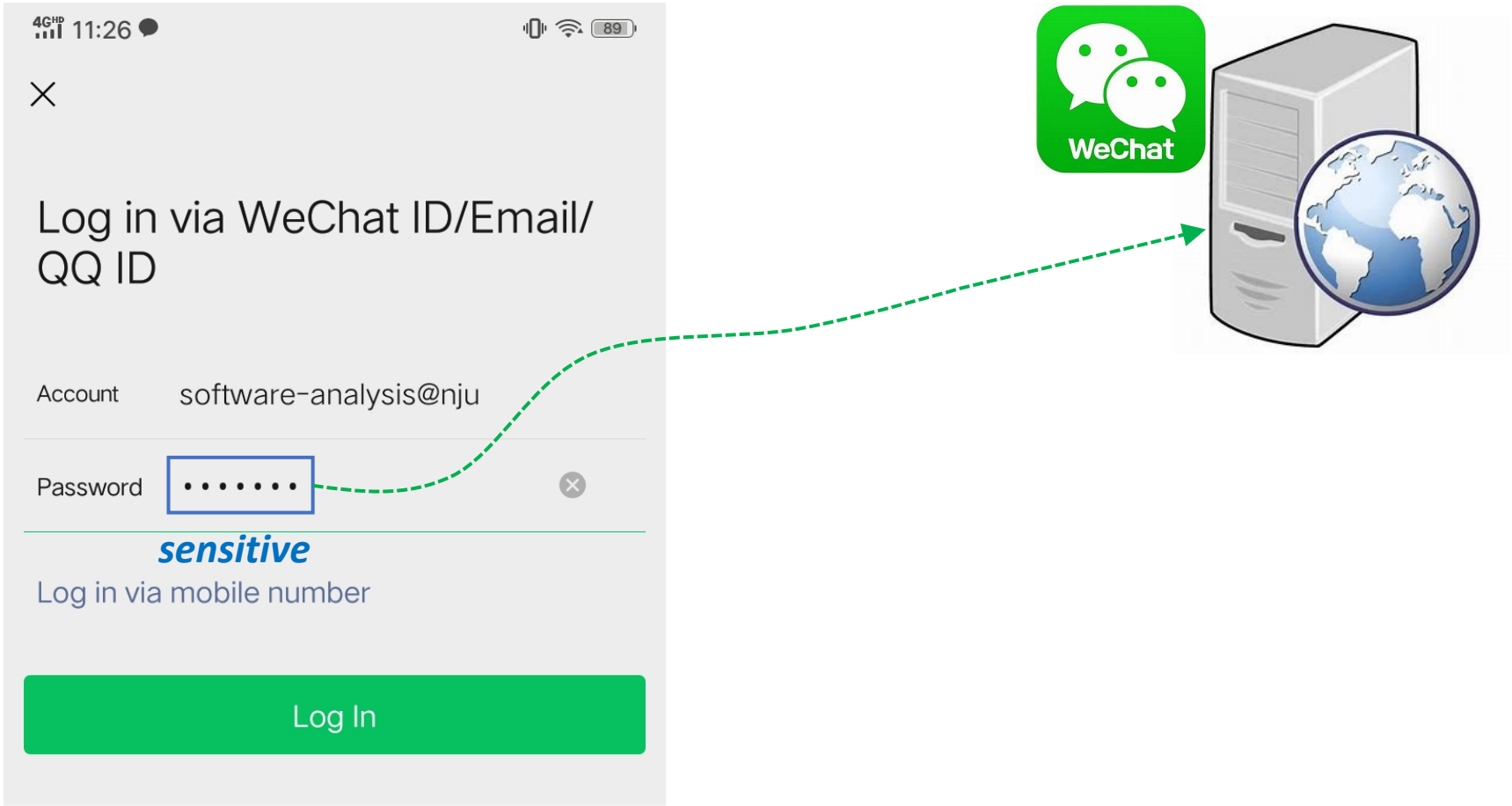


1. **Information Flow Security**
2. Confidentiality and Integrity
3. Explicit Flows and Covert Channels
4. Taint Analysis

Information Flow: An Example



Information Flow: An Example



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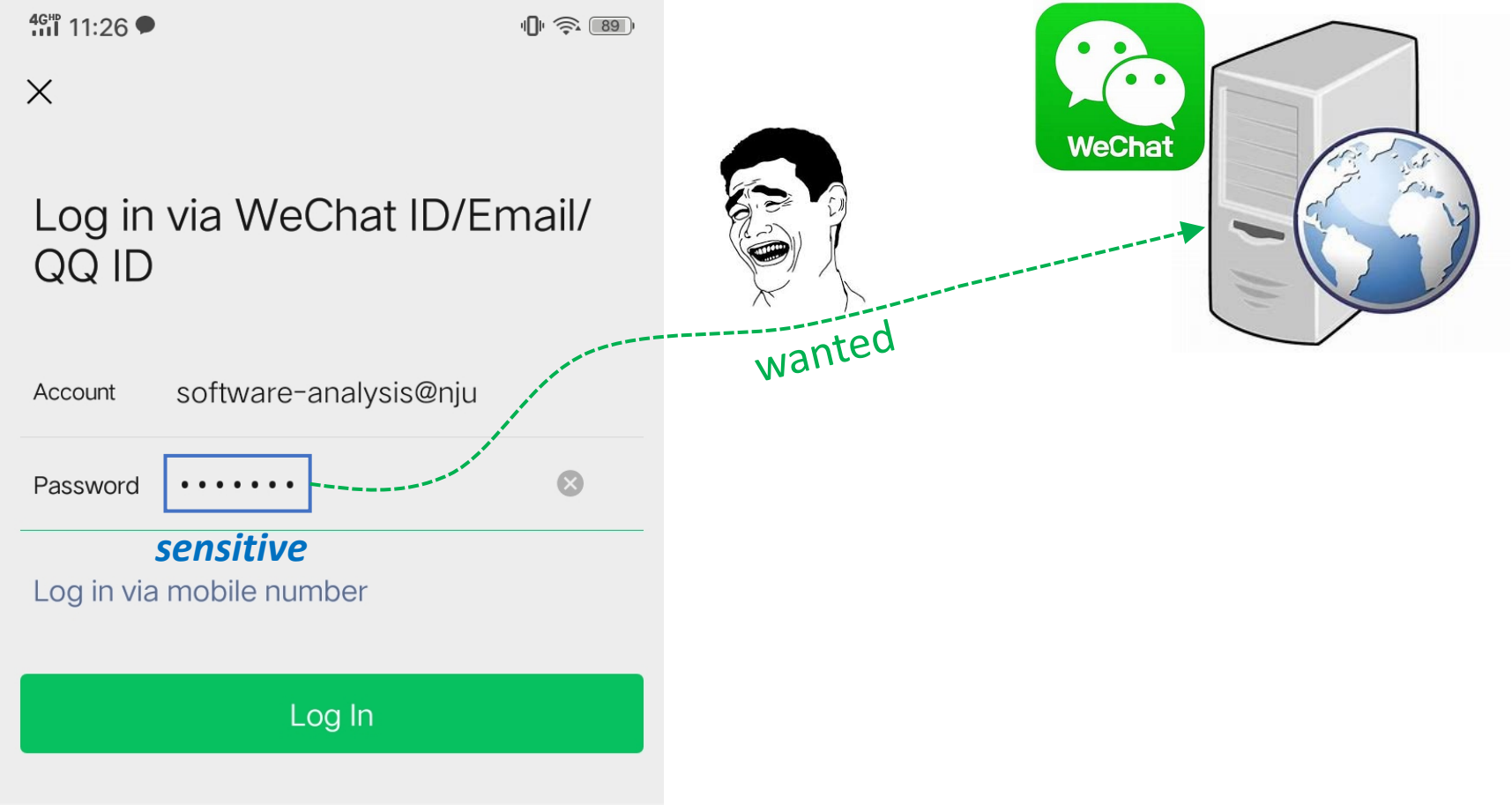

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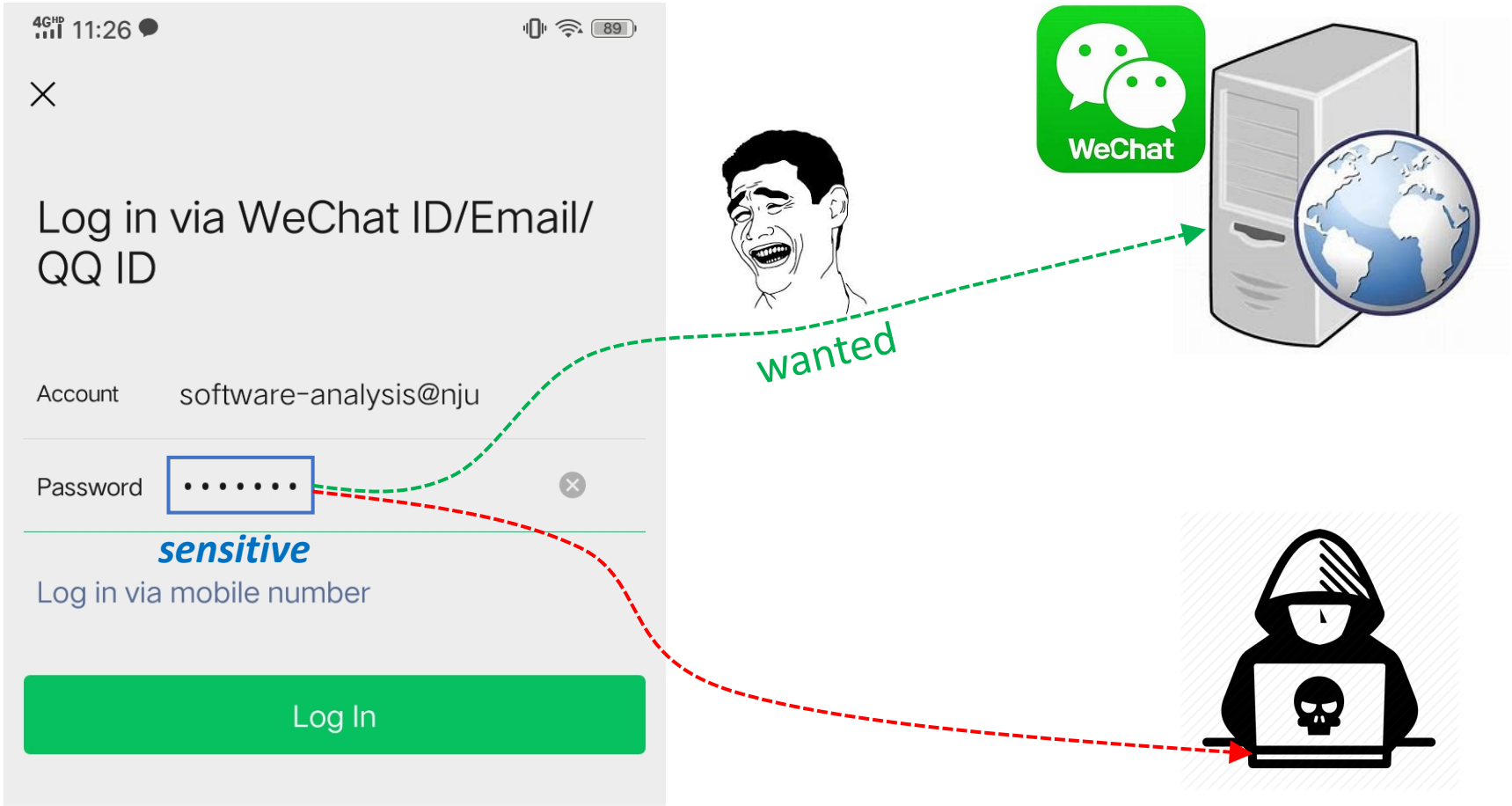

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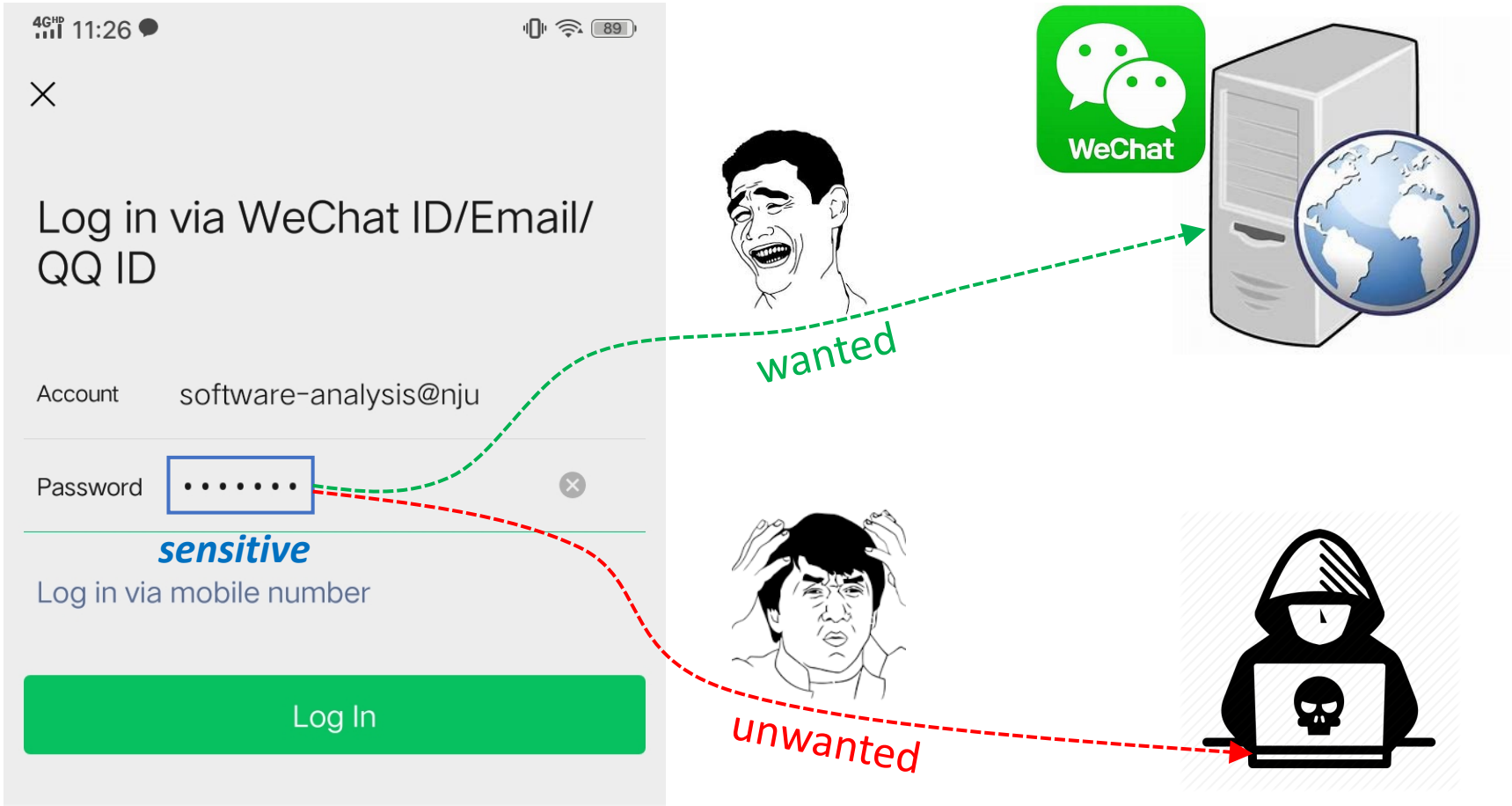
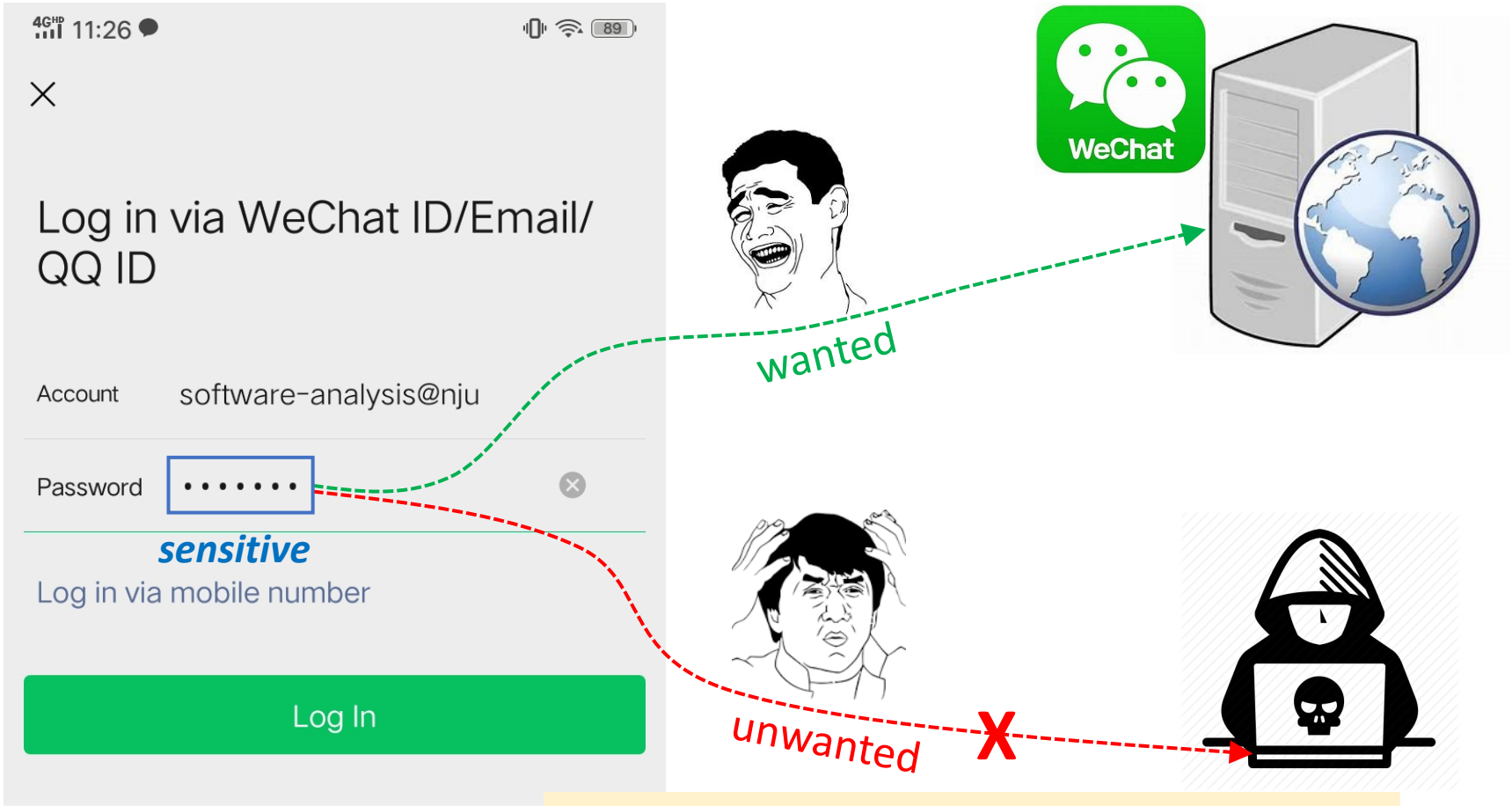


Information Flow Security: Motivation



Prevent unwanted information flow

Protect information security

Access Control vs. Information Flow Security

- Access control (a standard way to protect sensitive data)
  - Checks if the program has the rights/permissions to access certain information
  - Concerns how information is **accessed**

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"*A practical system needs both **access** and **flow control** to satisfy all security requirements.*"
— D. Denning, 1976

Information Flow*

- Information flow: if the information in variable x is transferred to variable y, then there is information flow $x \rightarrow y$

* Dorothy E. Denning and Peter J. Denning, "*Certification of Programs for Secure Information Flow*". CACM 1977.

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- Examples


```
y = x;
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```
a = x;
b.f = a;
y = b.f;
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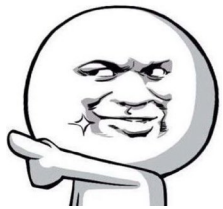
Looks like pointer analysis?
You will see …



*Dorothy E. Denning and Peter J. Denning, "*Certification of Programs for Secure Information Flow*". CACM 1977.

Information Flow Security

Connects information flow to security

- Classifies program variables into different security levels
- Specifies permissible flows between these levels, i.e., information flow policy

Security Levels (Classes)

- The most basic model is two-level policy, i.e., a variable is classified into one of two security levels:
  1. H, meaning *high* security, secret information
  2. L, meaning *low* security, public observable information

```
h = getPassword(); // h is high security
broadcast(l);      // l is low security
```

Security Levels (Classes)

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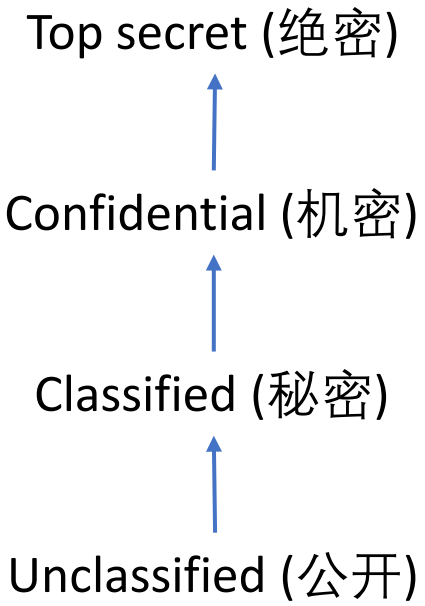
- Security levels can be modeled as *lattice**
  - L ≤ H

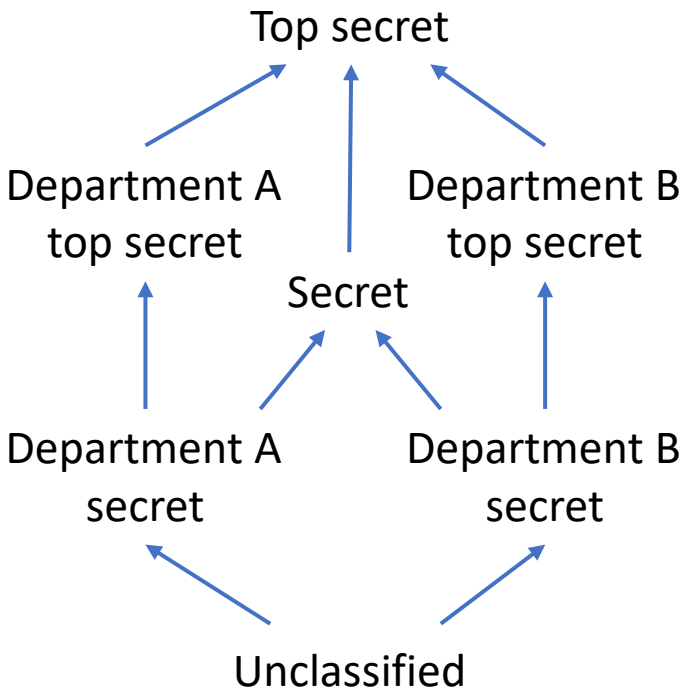
*Dorothy E. Denning, "*A Lattice Model of Secure Information Flow*". CACM 1976.

More Complicated Security Levels

- China classification



- A (possible) business classification



Information Flow Policy

- Restricts how information flows between different security levels

Information Flow Policy

- Restricts how information flows between different security levels
- Noninterference policy*
  - Requires the information of high variables have no effect on (i.e., should not interfere with) the information of low variables
  - Intuitively, you should not be able to conclude anything about high information by observing low variables

*J. A. Goguen and J. Meseguer, "*Security policies and security models*". S&P 1982.

Noninterference

- Requires the information of high variables have no effect on (i.e., should not interfere with) the information of low variables

✔ • $x_H = y_H$

✔ • $x_L = y_L$

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✘ • $x_L = y_H$

? • $x_H = y_L$

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✓ • $x_L = y_L$

✗ • $x_L = y_H$

✓ • $x_H = y_L$

? • $x_L = y_L + z_H$

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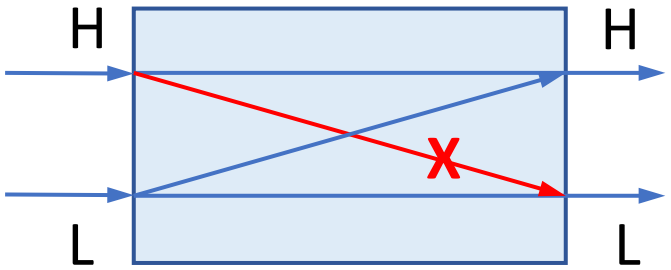
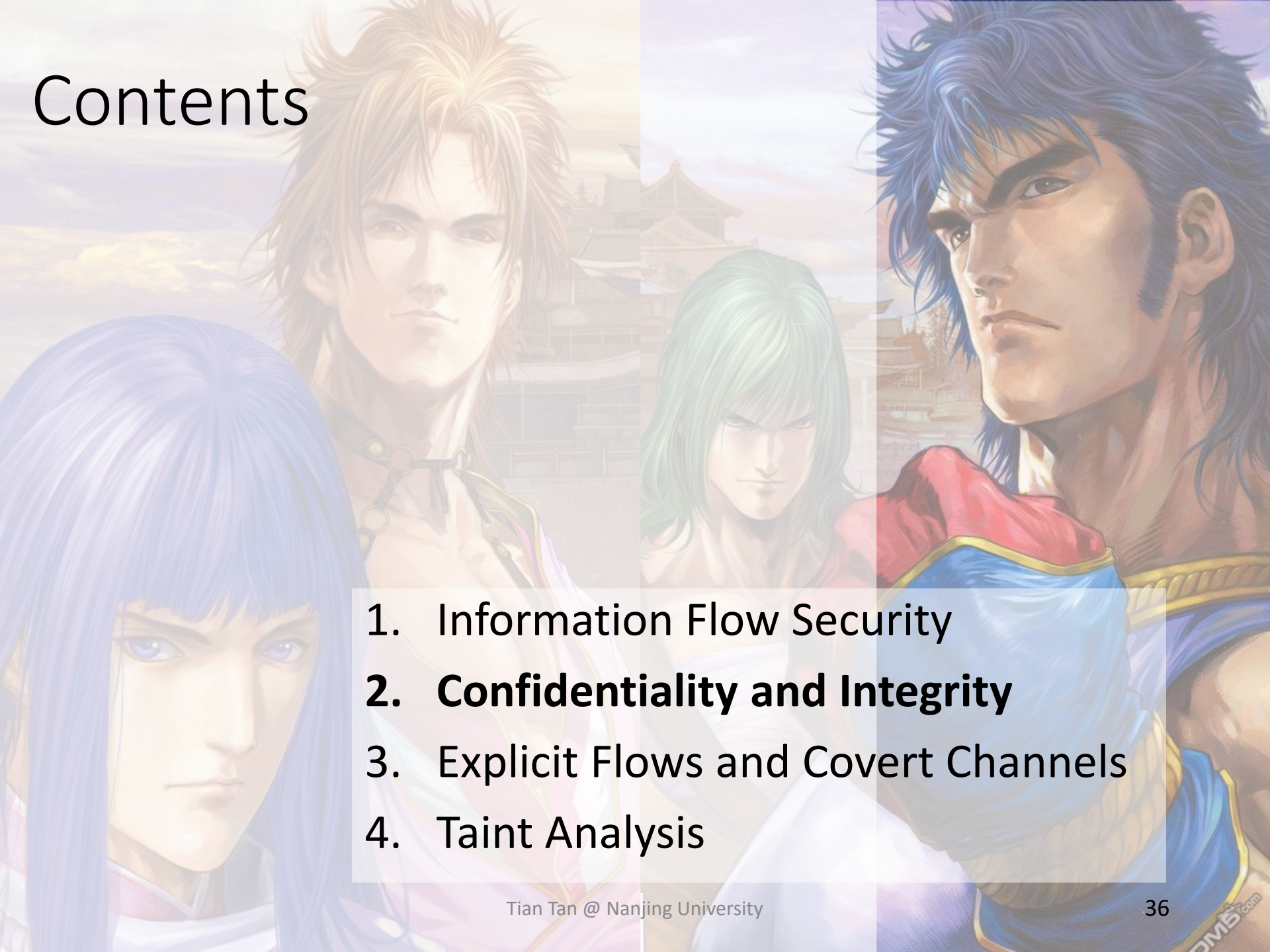


Ensures that information flows only upwards in the lattice

Contents



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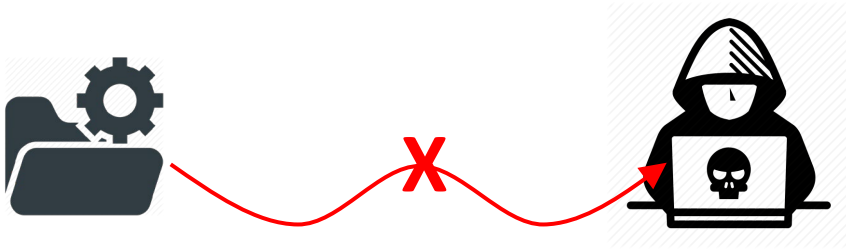
- Confidentiality
  - Prevent secret information from being leaked



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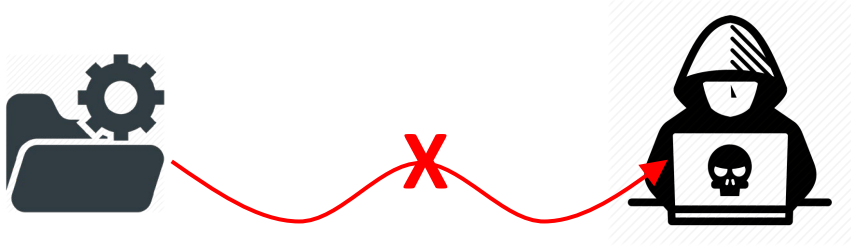
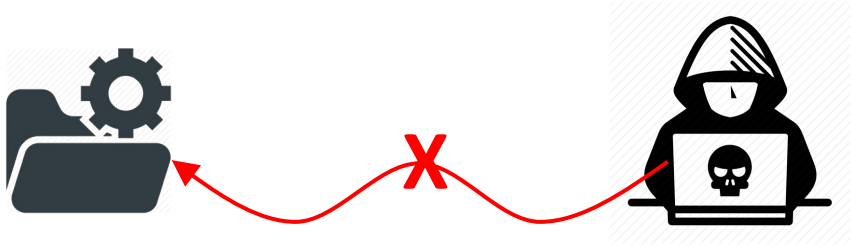


Information flow security from another perspective

- Integrity
  - Prevent untrusted information from corrupting (trusted) critical information



Integrity

- Prevent untrusted information from corrupting (trusted) critical information[1]

```
x = readInput(); // untrusted
cmd = "..." + x;
execute(cmd); // critical (trusted)
```

1. Ken Biba, "*Integrity Considerations for Secure Computer Systems*". Technical Report, ESD-TR-76-372, USAF Electronic Systems Division, Bed-ford, MA, 1977.

Integrity

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- Injection errors (#1 cause of vulnerabilities in 2013-2019[2])
  - Command injection
  - SQL injection
  - XSS attacks
  - …

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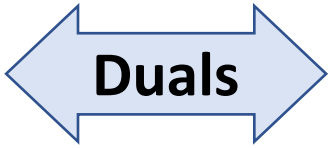
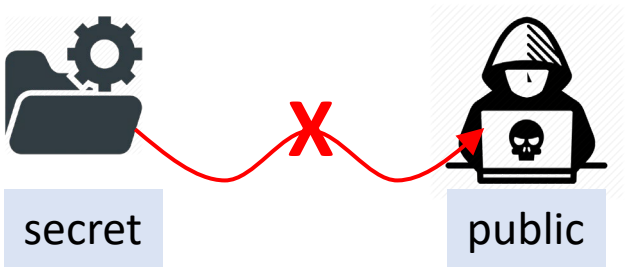
Confidentiality and Integrity

Confidentiality  **Integrity**

- Security classification
  - Secret (**H**igh secret)
  - Public (**L**ow secret)

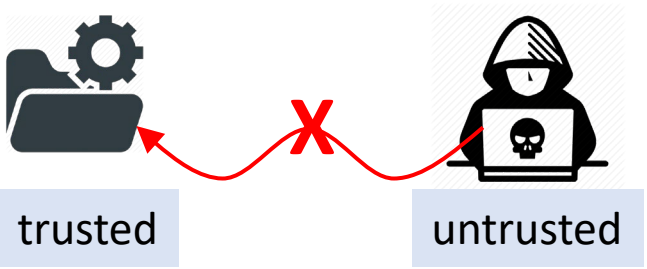
H
↑
L



- Read protection

- Security classification
  - Trusted (**H**igh integrity)
  - Untrusted (**L**ow integrity)

L
↑
H



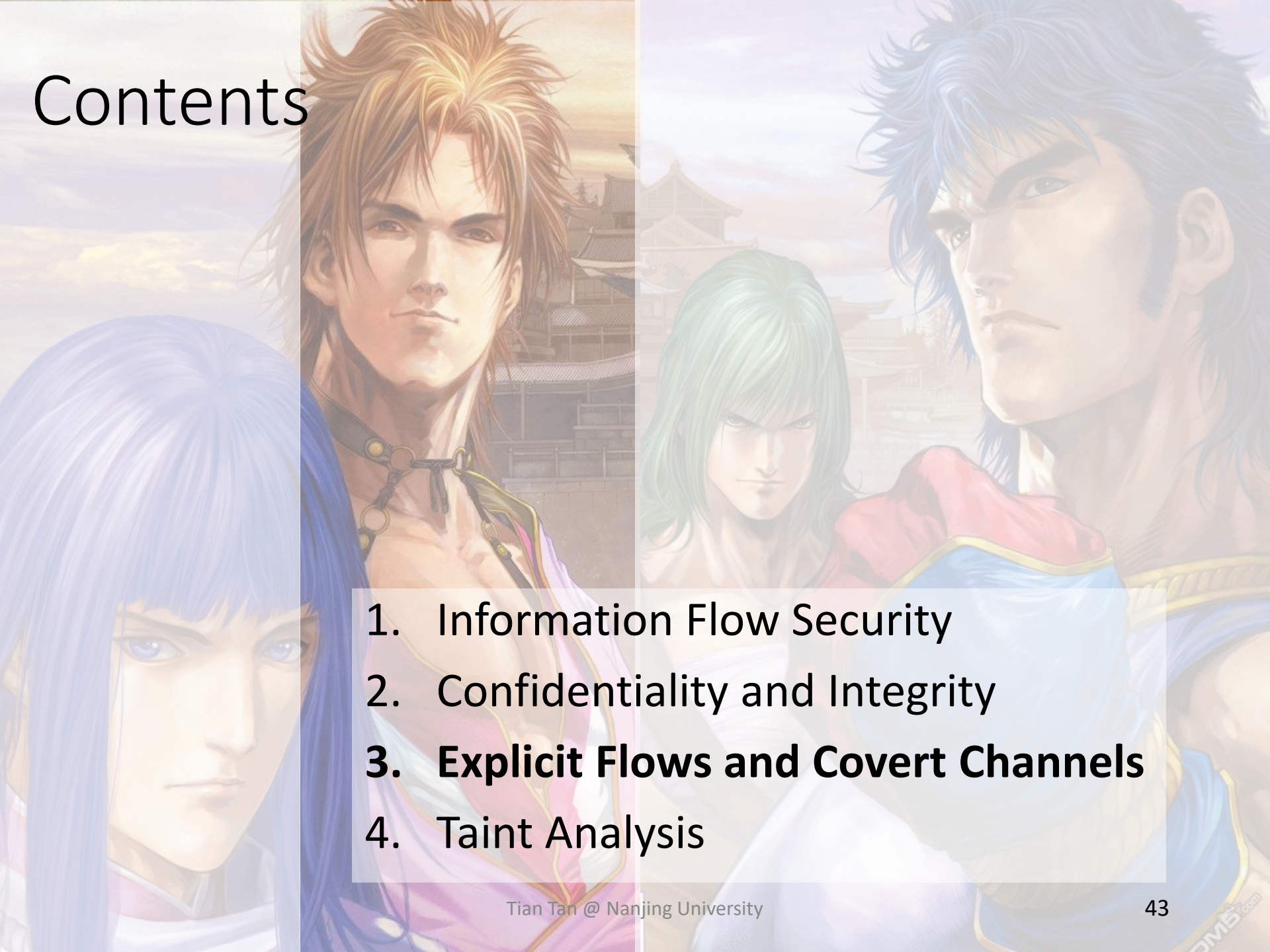
- Write protection

Integrity, Broad Definition

- To ensure the correctness, completeness, and consistency of data

- Correctness
  - E.g., for information flow integrity, the (trusted) critical data should not be corrupted by untrusted data
- Completeness
  - E.g., a database system should store all data completely
- Consistency
  - E.g., a file transfer system should ensure that the file contents of both ends (sender and receiver) are identical

Contents



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How Does Information Flow

- $x_H = y_H$
- $x_L = y_H$
- $x_L = y_L + z_H$

We have seen how information flows through direct copying. This is called explicit flow.

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We have seen how information flows through direct copying. This is called explicit flow.

Is this the only way of information flow?

Does Secret Information Leak?

```
secret_H = getSecret();
if (secret_H < 0)
    publik_L = 1;
else
    publik_L = 0;
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Implicit Flows

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- This kind of information flow is called **implicit flow**, which may arise when the control flow is affected by secret information.
- Any differences in side effects under secret control encode information about the control, which may be publicly observable and leak secret information.

Implicit Flows

Are there *any other* kinds of information flows?

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Does Secret Information Leak?

? `while (secret_H < 0) { … };`

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Leak, we can conclude that secret is negative if the program does not terminate

?

```
if (secret_H < 0)
  for (int i = 0; i < 1000000; ++i) { … };
```

Does Secret Information Leak?

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if (secret_H < 0)
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```
int sa_H[] = getSecretArray();
sa_H[secret_H] = 0;
```

Does Secret Information Leak?

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while (secret_H < 0) { … };
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Leak, we can conclude that secret is negative if we observe the exception

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Leak, exception may reveal that secret is negative

Covert/Hidden Channels

- Mechanisms for signalling information through a computing system are known as ***channels***.
- Channels that exploit a mechanism whose primary purpose is not information transfer are called ***covert channels****.

*Butler W. Lampson, "*A Note on the Confinement Problem*". CACM 1973.

Covert/Hidden Channels

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- Channels that exploit a mechanism whose primary purpose is not information transfer are called ***covert channels****.

- Implicit flows

```
if (secret_H < 0) p_L = 1; else p_L = 0;
```

  signal information through the control structure of a program

- Termination channels

```
while (secret_H < 0) { … };
```

  signal information through the (non)termination of a computation

- Timing channels

```
if (secret_H < 0) for (…) { … };
```

  signal information through the computation time

- Exceptions

```
if (secret_H < 0) throw new Exception("…");
```

  signal information through the exceptions

- …

∗Butler W. Lampson, "*A Note on the Confinement Problem*". CACM 1973.

Explicit Flows and Covert Channels

- Explicit flows generally carry more information than covert channels, so we focus on explicit flows

```
int secret_H = getSecret();
int publik_L = secret_H;
```

Explicit flow:
transmits 32 bits of information

```
int secret_H = getSecret();
if (secret_H % 2 == 0)
    publik_L = 1;
else
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Implicit flow:
transmits 1 bit of information

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How to prevent unwanted information flows, i.e., enforce information flow policies?

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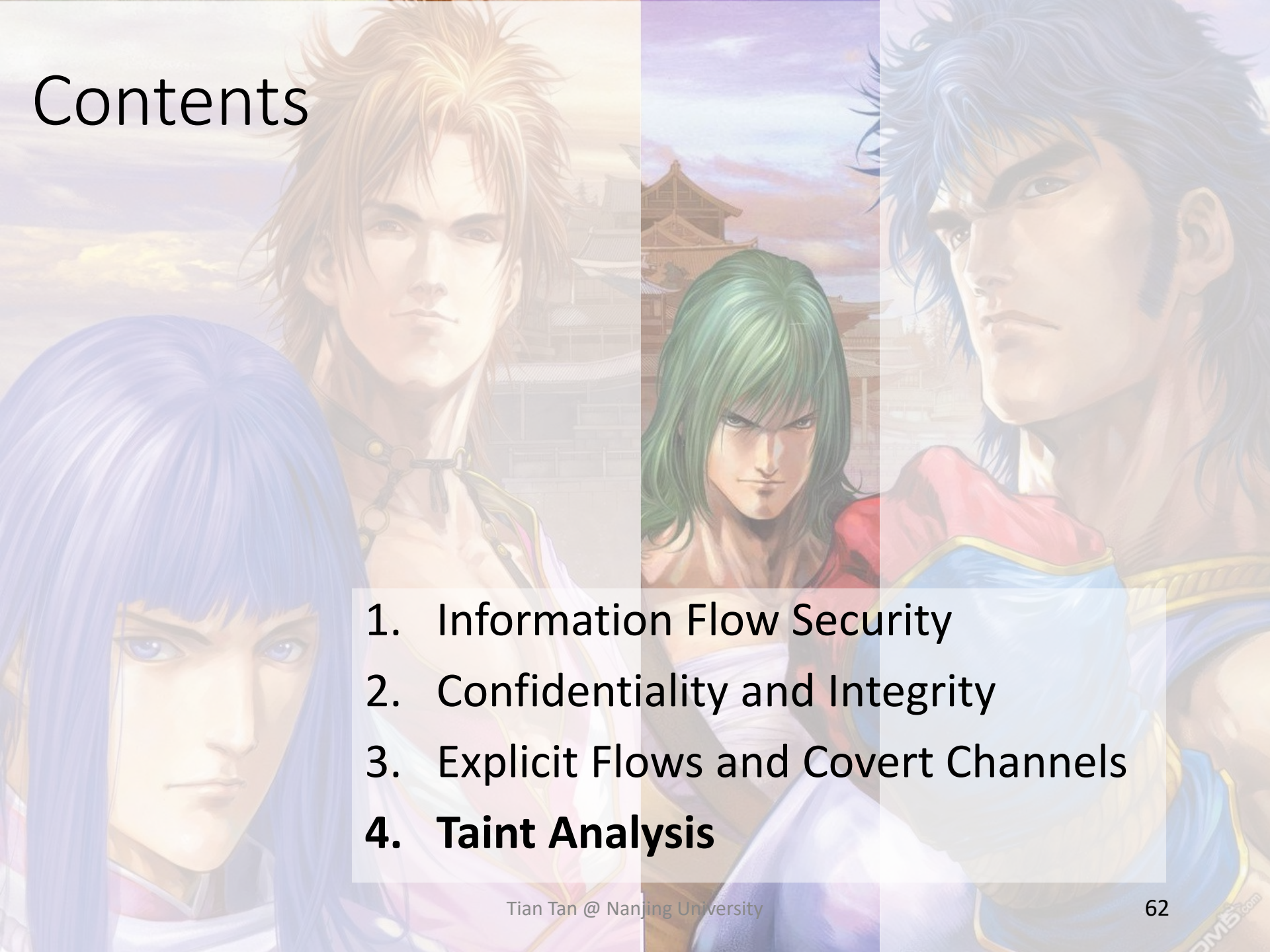

1. Information Flow Security
2. Confidentiality and Integrity
3. Explicit Flows and Covert Channels
4. **Taint Analysis**

Taint Analysis

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  - Data of interest, some kinds of labels are associated with the data, called **tainted data**
  - Other data, called untainted data

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  - Other data, called untainted data
- Sources of tainted data is called **sources**. In practice, tainted data usually come from the return values of some methods (regarded as sources).
- Taint analysis tracks how tainted data flow through the program and observes if they can flow to locations of interest (called **sinks**). In practice, sinks are usually some sensitive methods.

Taint Analysis: Two Applications

- Confidentiality
  - Source: source of secret data
  - Sink: leakage
  - Information leaks

```
x = getPassword(); // source
y = x;
log(y); // sink
```

- Integrity
  - Source: source of untrusted data
  - Sink: critical computation
  - Injection errors

```
x = readInput(); // source
cmd = "..." + x;
execute(cmd); // sink
```

Taint analysis can detect **both** unwanted information flows

Taint Analysis

- “Can tainted data flow to a sink?”

Taint Analysis

- “Can tainted data flow to a sink?”

Or, in another way

- “Which tainted data a pointer (at a sink) can point to?”

Taint and Pointer Analysis, Together*

The essence of taint analysis/pointer analysis is to track how tainted data/abstract objects flow through the program

- Treats tainted data as (artificial) objects
- Treats sources as allocation sites (of tainted data)
- Leverages pointer analysis to propagate tainted data

* Neville Grech and Yannis Smaragdakis, "*P/Taint: Unified Points-to and Taint Analysis*". OOPSLA 2017.

Domains and Notations

Variables:	$x, y \in \mathrm{V}$
Fields:	$f, g \in \mathrm{F}$
Objects:	$o_i, o_j \in \mathrm{O}$
Tainted data:	$t_i, t_j \in \mathrm{T} \subset \mathrm{O}$
Instance fields:	$o_i.f, o_j.g \in \mathrm{O} \times \mathrm{F}$
Pointers:	$\mathrm{Pointer} = \mathrm{V} \cup (\mathrm{O} \times \mathrm{F})$
Points-to relations:	$pt : \mathrm{Pointer} \rightarrow \mathcal{P}(\mathrm{O})$

- t_i denotes the tainted data from call site i
- $\mathcal{P}(\mathrm{O})$ denotes the powerset of O
- $pt(p)$ denotes the points-to set of p

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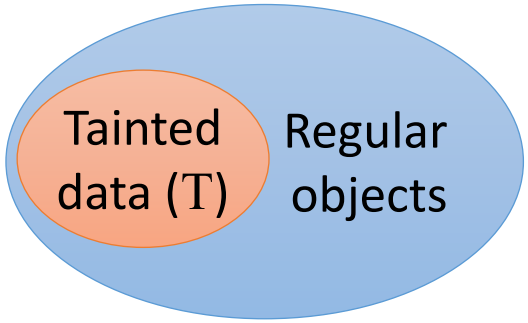

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Taint Analysis: Inputs & Outputs

- Inputs
  - $Sources$: a set of source methods (the calls to these methods return tainted data)
  - $Sinks$: a set of sink methods (that tainted data flow to these methods violates security polices)

- Outputs
  - $TaintFlows$: a set of pairs of tainted data and sink methods

    E.g., $\langle t_i, m \rangle \in TaintFlows$ denotes that the tainted data from call site i (which calls a source method) may flow to sink method m

Rules: Call

- Handles sources (generates tainted data)

Kind	Statement	Rule
Call	`l: r = x.k(a1,…,an)`	$\frac{l \to m \in CG \quad m \in Sources}{t_l \in pt(r)}$

Rules (Same as Pointer Analysis)

Kind	Statement	Rule
New	`i: x = new T()`	$\dfrac{}{o_i \in pt(x)}$
Assign	`x = y`	$\dfrac{o_i \in pt(y)}{o_i \in pt(x)}$
Store	`x.f = y`	$\dfrac{o_i \in pt(x),\ o_j \in pt(y)}{o_j \in pt(o_i.f)}$
Load	`y = x.f`	$\dfrac{o_i \in pt(x),\ o_j \in pt(o_i.f)}{o_j \in pt(y)}$
Call	`l: r = x.k(a1,…,an)`	$\dfrac{\begin{array}{c} o_i \in pt(x),\ m = \text{Dispatch}(o_i, \text{k}) \\ o_u \in pt(aj), 1 \le j \le n \\ o_v \in pt(m_{ret}) \\ o_i \in pt(m_{this}) \\ o_u \in pt(m_{pj}), 1 \le j \le n \end{array}}{o_v \in pt(r)}$

Propagate objects and tainted data

Rules: Call

- Handles sources (generates tainted data)

Kind	Statement	Rule
Call	`l: r = x.k(a1,…,an)`	$\dfrac{l \to m \in CG \quad m \in Sources}{t_l \in pt(r)}$

- Handles sinks (generates taint flow information)

Kind	Statement	Rule
Call	`l: r = x.k(a1,…,an)`	$\dfrac{l \to m \in CG \quad m \in Sinks \quad \exists i, 1 \le i \le n : t_j \in pt(ai)}{\langle t_j, m \rangle \in TaintFlows}$

Taint Analysis: An Example

```
1  void main() {
2    A x = new A();
3    String pw = getPassword();
4    A y = x;
5    x.f = pw;
6    String s = y.f;
7    log(s);
8  }
9  String getPassword() {
10   …
11   return new String(…);
12 }
13 class A {
14   String f;
15 }
```

Sources: { getPassword() }

Sinks: { log(String) }

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Variable	Object
x	o_2

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Variable	Object
x	o_2
pw	o_{11}

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Sources: { getPassword() }

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Variable	Object
x	o_2
pw	o_{11}, t_3

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pw	o_{11}, t_3
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Field	**Object**
o_2.f	o_{11}, t_3

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Field	**Object**
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Sources: { getPassword() }

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TaintFlows: { $\langle t_3, \log(\text{String})\rangle$ }

Variable	Object
x	o_2
pw	o_{11}, t_3
y	o_2
s	o_{11}, t_3
Field	**Object**
o_2.f	o_{11}, t_3

Kind	Statement	Rule
Call	l: r = x.k(a1,…,an)	$\dfrac{l \to m \in CG \quad m \in Sinks \quad \exists i, 1 \le i \le n: t_j \in pt(ai)}{\langle t_j, m\rangle \in TaintFlows}$

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Variable	Object
x	o_2
pw	o_{11}, t_3
y	o_2
s	o_{11}, t_3
Field	**Object**
$o_2.\texttt{f}$	o_{11}, t_3

The X You Need To Understand in This Lecture

- Concept of information flow security
- Confidentiality and integrity
- Explicit flows and covert channels
- Use taint analysis to detect unwanted information flow

软件分析

南京大学

计算机科学与技术系

程序设计语言与静态分析研究组

李樾 谭添