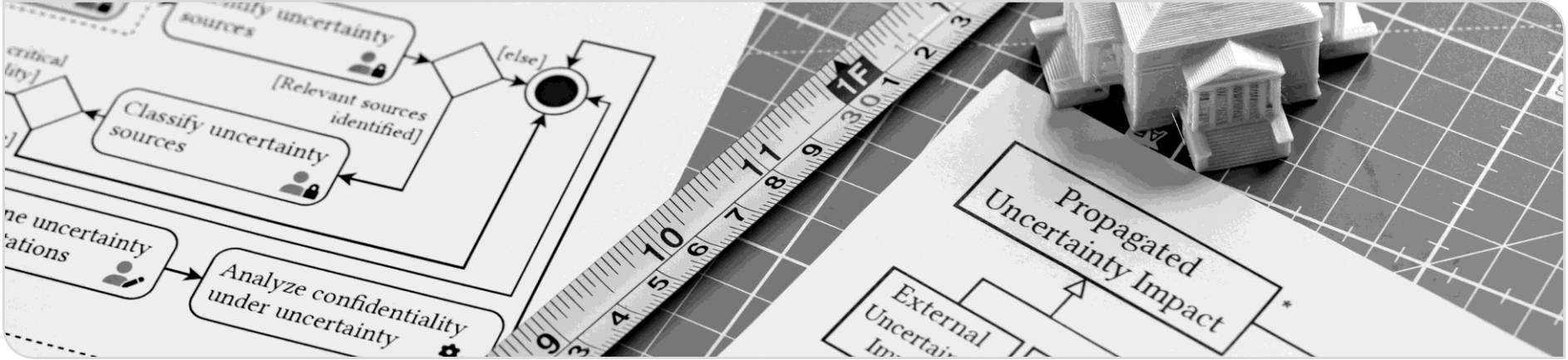
Software Architecture, Confidentiality, and Uncertainty
– A (very) short summary

Dr.-Ing. Sebastian Hahner

CyberSec Seminar, April 8th, 2025

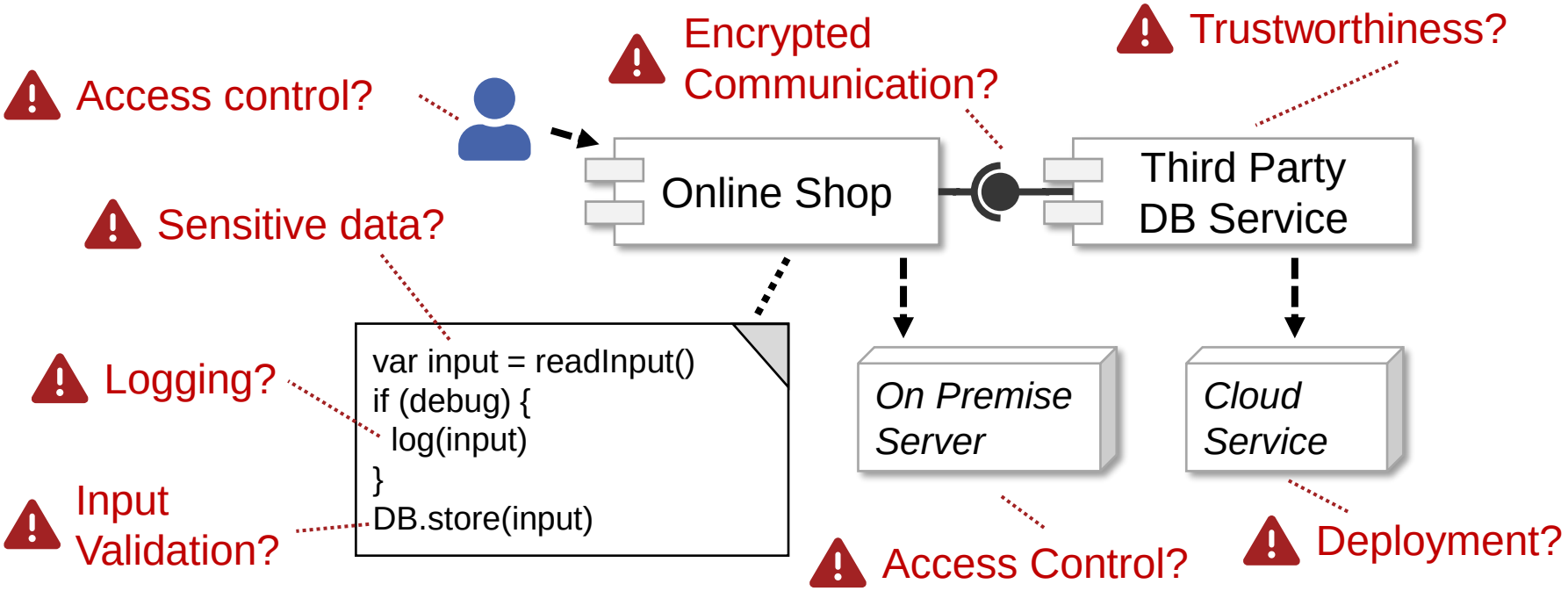


Architecture?

Architecture-Based and Uncertainty-Aware Confidentiality Analysis

Architecture and Confidentiality Violations?

Architecture-Based and Uncertainty-Aware Confidentiality Analysis



Data Breaches, Cyber Attacks and Confidentiality

TECHNOLOGY | CYBERSECURITY

What's Behind the Increase in Data Breaches?

One reason: Ransomware gangs are on the rise, allowing even criminals with minimal computer knowledge to get into the game

[1]

TECH • LINKEDIN

Massive data leak exposes 700 million Li

TICKETMASTER CONFIRMS DATA BREACH IMPACTING 560 MILLION CUSTOMERS

Pierluigi Paganini June 01, 2024

[2]

[3]

Russia accused of EU and Nato cyber-attacks

9 September 2024

[4]

Chat app Knuddels fined €20,000 for GDPR breach

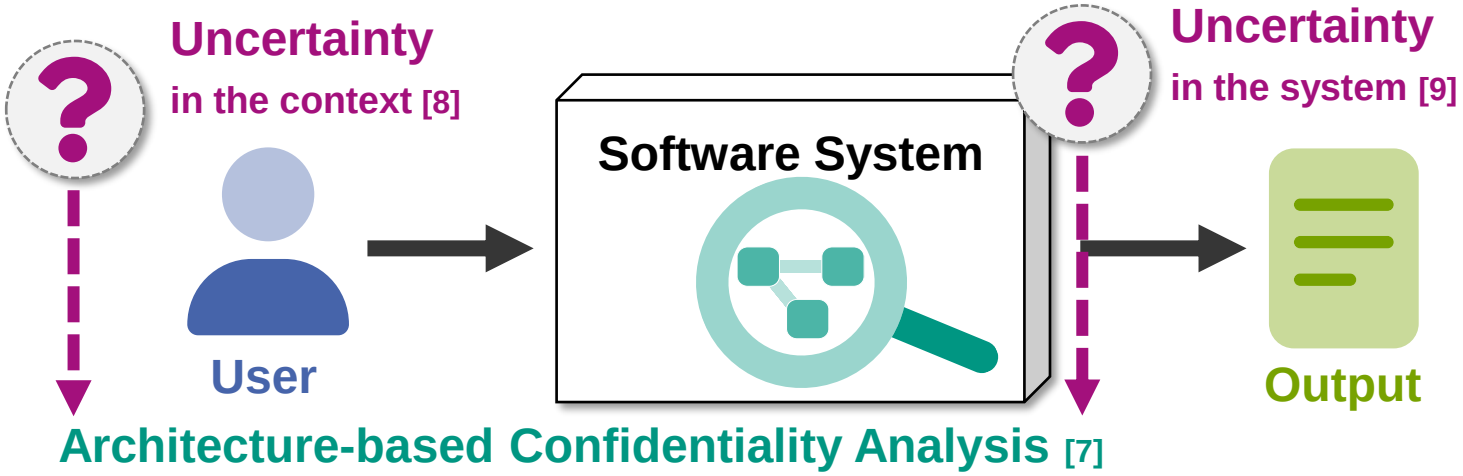
Luke Irwin 29th November 2018

[5]

Confidentiality: "property that information is not made available or disclosed to unauthorized individuals, entities, or processes" [6]

[1] Wall Street Journal, https://www.wsj.com/tech/cybersecurity/why-are-cybersecurity-data-breaches-still-rising-2f08866c, 2024 (last checked: 03.12.24)
[2] FORTUNE, https://fortune.com/2021/06/30/linkedin-data-theft-700-million-users-personal-information-cybersecurity, 2021(last checked: 03.12.24)
[3] Security Affairs, https://securityaffairs.com/163999/data-breach/ticketmaster-confirms-data-breach.html, 2024 (last checked: 03.12.24)
[4] BBC, https://www.bbc.com/news/articles/c984zenjkz5o, 2024 (last checked: 03.12.24)
[5] IT Governance, https://www.itgovernance.eu/blog/en/chat-app-knuddels-fined-e20000-for-gdpr-breach, 2018 (last checked: 03.12.24)
[6] ISO/IEC 27000:2018(E) Information technology – Security techniques – Information security management systems – Overview and vocabulary, 2018.

Software Architecture Analysis under Uncertainty



Uncertainty: "deficiency of information related to, understanding or knowledge of, an event, its consequence, or likelihood" [6]

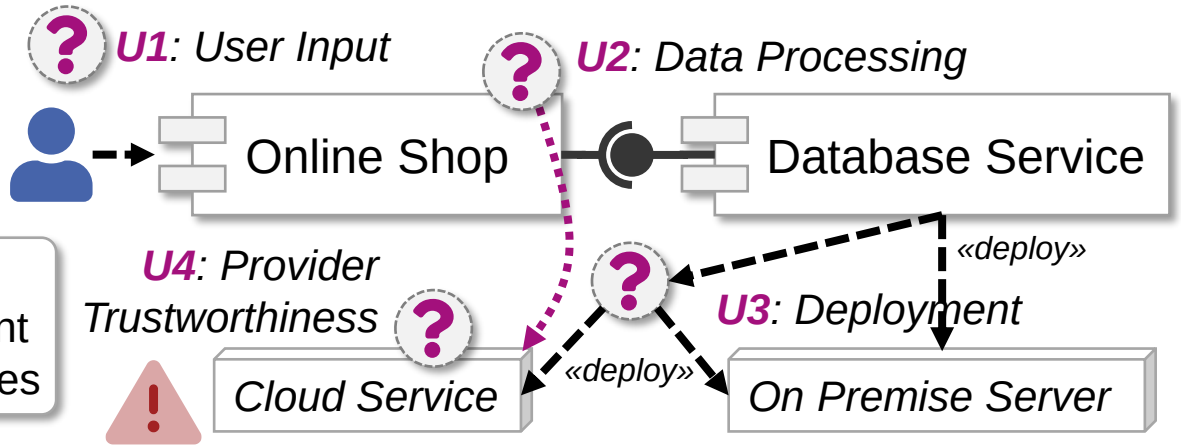
[7] S. Seifermann, et al., "Detecting violations of access control and information flow policies in data flow diagrams", JSS, vol. 184, Elsevier, 2022.
[8] D. Garlan, "Software engineering in an uncertain world", FoSER , ACM, 2010.
[9] S. McConnell, "Software project survival guide", Microsoft Press, 1998.
[6] ISO/IEC 27000:2018(E) Information technology – Security techniques – Information security management systems – Overview and vocabulary, 2018.

Challenges of Confidentiality and Uncertainty

Challenge 1
Understanding, describing, and classifying uncertainty

Challenge 2
Identifying relevant uncertainty sources

Confidentiality Requirement: Protect personal user data.



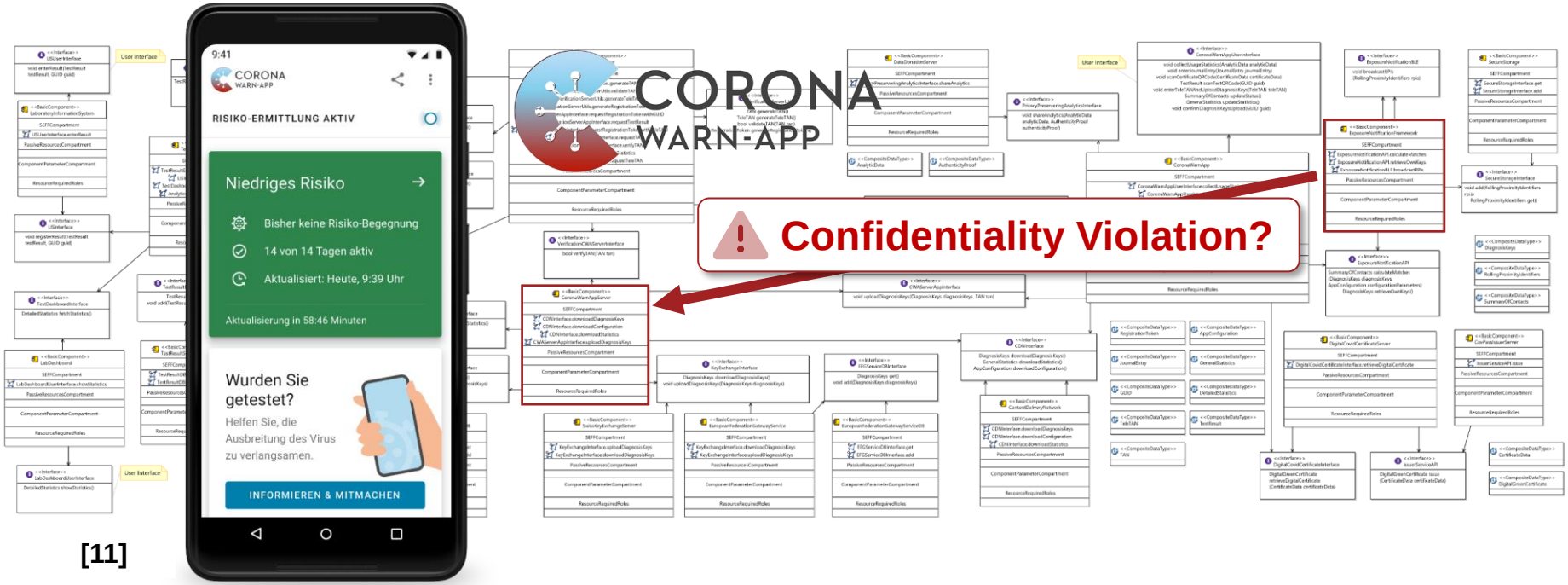
Challenge 3
Predicting the impact of uncertainty

Challenge 4
Identifying confidentiality violations due to uncertainty

Gap: lack of means to identify, describe, and analyze uncertainty regarding confidentiality at design time

[10] S. M. Hezavehi, et al., "Uncertainty in Self-adaptive Systems: A Research Community Perspective," ACM TAAS., vol. 15, no. 4, 2021.

Enabling Architectural Confidentiality Analysis



[11]

[11] Robert Koch Institute, Open-source Corona Warn App, documentation available online: https://github.com/corona-warn-app
[12] S. Hahner, et al., “Architecture-Based Uncertainty Impact Analysis to Ensure Confidentiality”, SEAMS, IEEE/ACM, 2023.

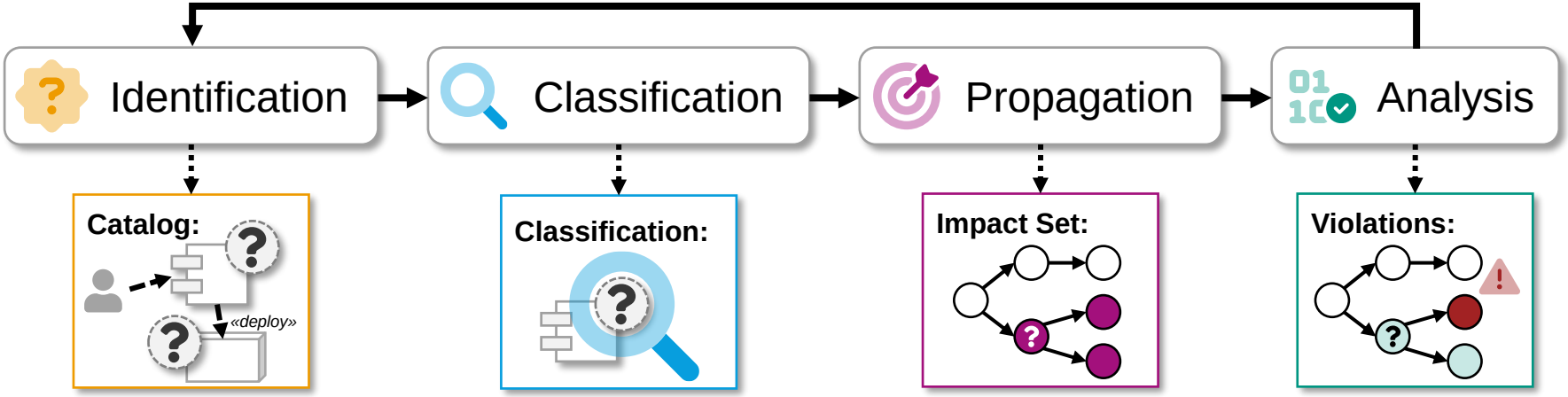
Security be like…

High precision is good…

but not without high recall.

⇨ **Architecture-Based and Uncertainty-Aware Confidentiality Analysis**

Uncertainty Management at Design Time [10,13]



Goal: Define a **catalog** and **classification** of uncertainty sources regarding confidentiality. Provide architectural analyses that **predict the impact** of uncertainty and **identify confidentiality violations** due to uncertainty.

[10] S. M. Hezavehi, et al., "Uncertainty in Self-adaptive Systems: A Research Community Perspective," ACM TAAS., vol. 15, no. 4, 2021.
[13] D. Weyns, …, S. Hahner, et al., "Towards a Research Agenda for Understanding and Managing Uncertainty in Self-Adaptive Systems," ACM SIGSOFT SEN, vol. 48, no. 4, 2023.

Contribution Overview

Identification and Classification of Uncertainty w.r.t. Confidentiality **C1**

[ECSA-C 2021] [ACM MODELS-C 2022] [Springer ICETE 2023] [ACM/IEEE MODELS-C 2024]

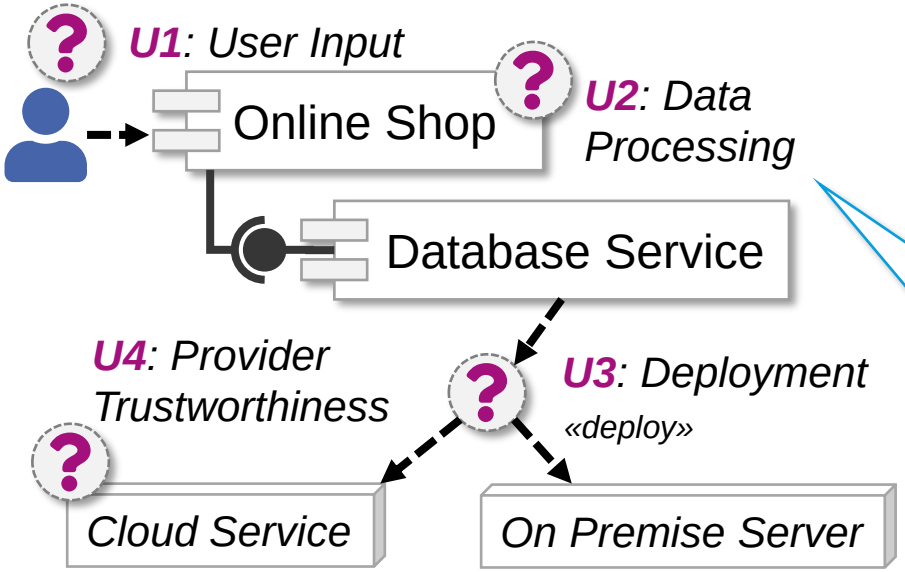
Architecture-Based Uncertainty Propagation and Impact Analysis **C2**

[IEEE/ACM SEAMS 2023] [IEEE/ACM SEAMS 2024]

Uncertainty-Aware Confidentiality Analysis **C3**

[IEEE SEAA 2022] [Springer ECSA 2022] [IEEE ICSA-C 2023] [Springer ECSA 2024]

C2 Uncertainty Impact Analysis



What do we have?

- Classified uncertainty sources [14]
- Mapping to data flow diagrams [15]

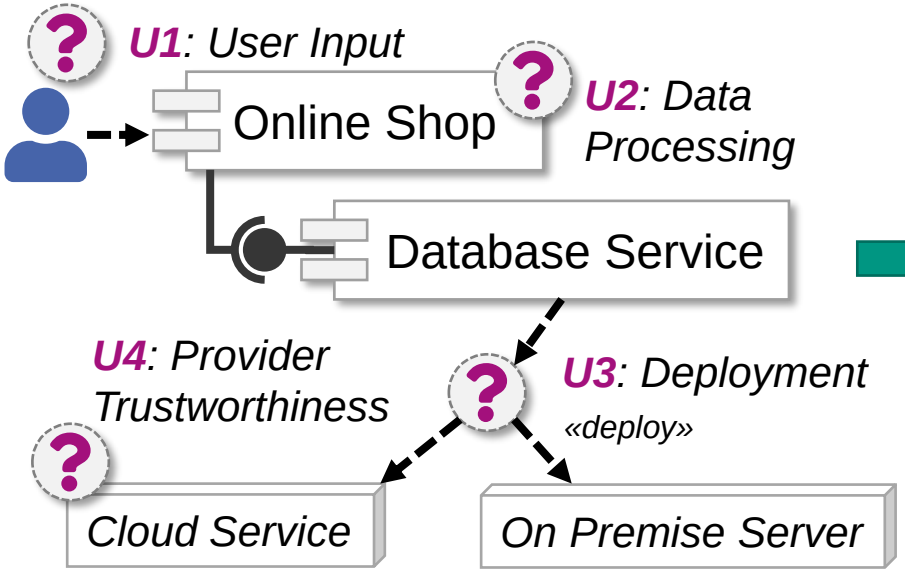
C1

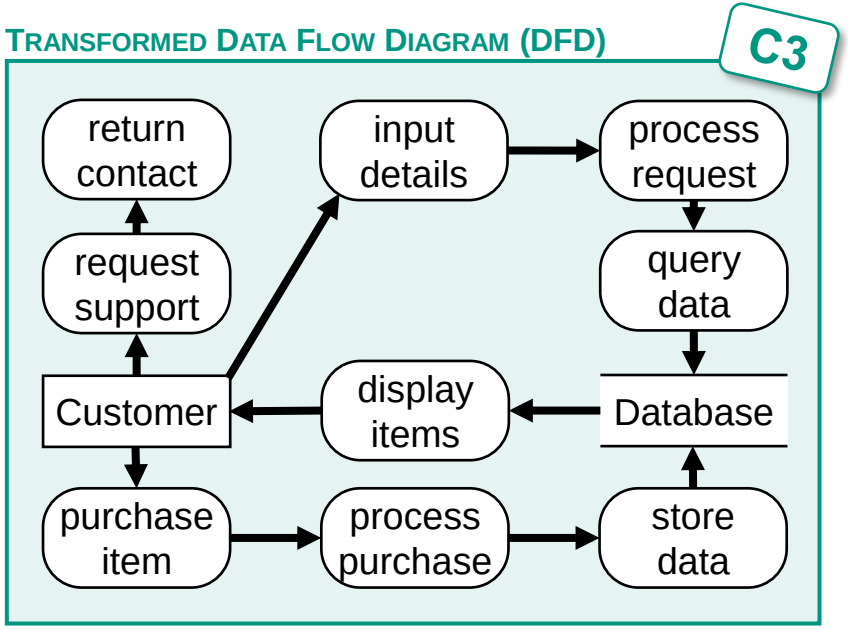
U2: Data Processing

Location:	*Behavior*
Type:	*Scenario Uncertainty*
Manageability:	*Fully Reducible*
Resolution:	*Design Time*

[14] S. Hahner, et al., "A Classification of Software-Architectural Uncertainty Regarding Confidentiality", ICETE, Springer, 2023.
[15] N. Boltz and S. Hahner, et al., "An Extensible Framework for Architecture-Based Data Flow Analysis for Information Security", ECSA, Springer, 2024.

C2 Uncertainty Impact Analysis





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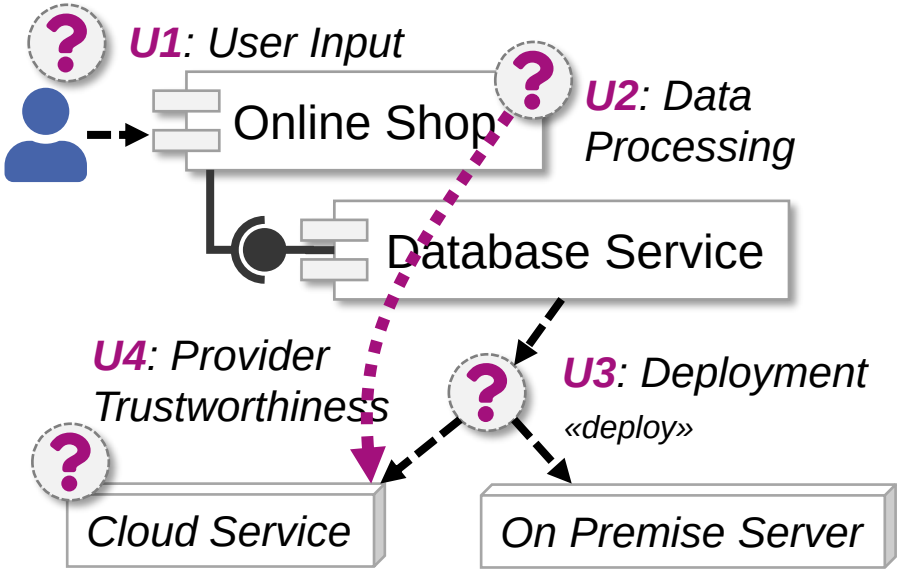

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What do we want?

- **Propagating** uncertainty sources
- Assessing the uncertainties' impact

How do we get there?

- Change impact analysis [16]
- Data flow-based propagation [7]

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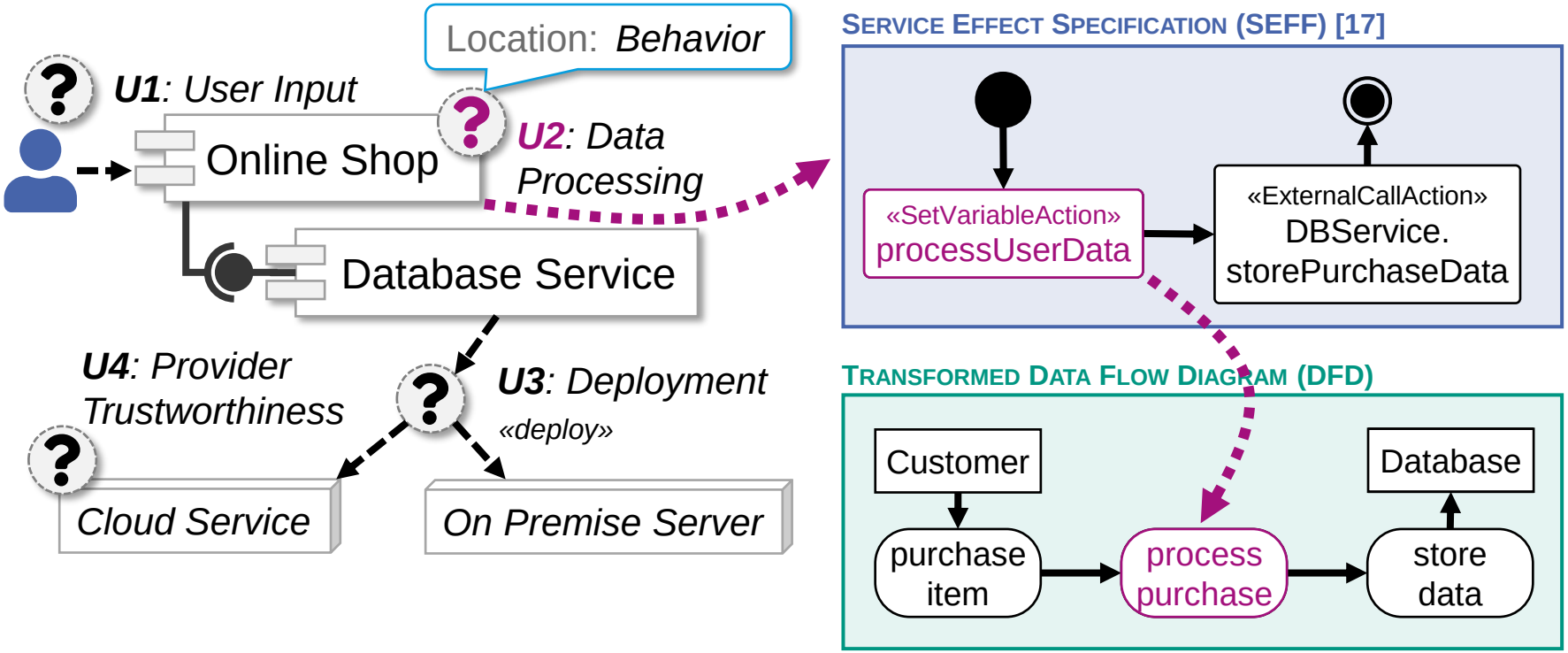
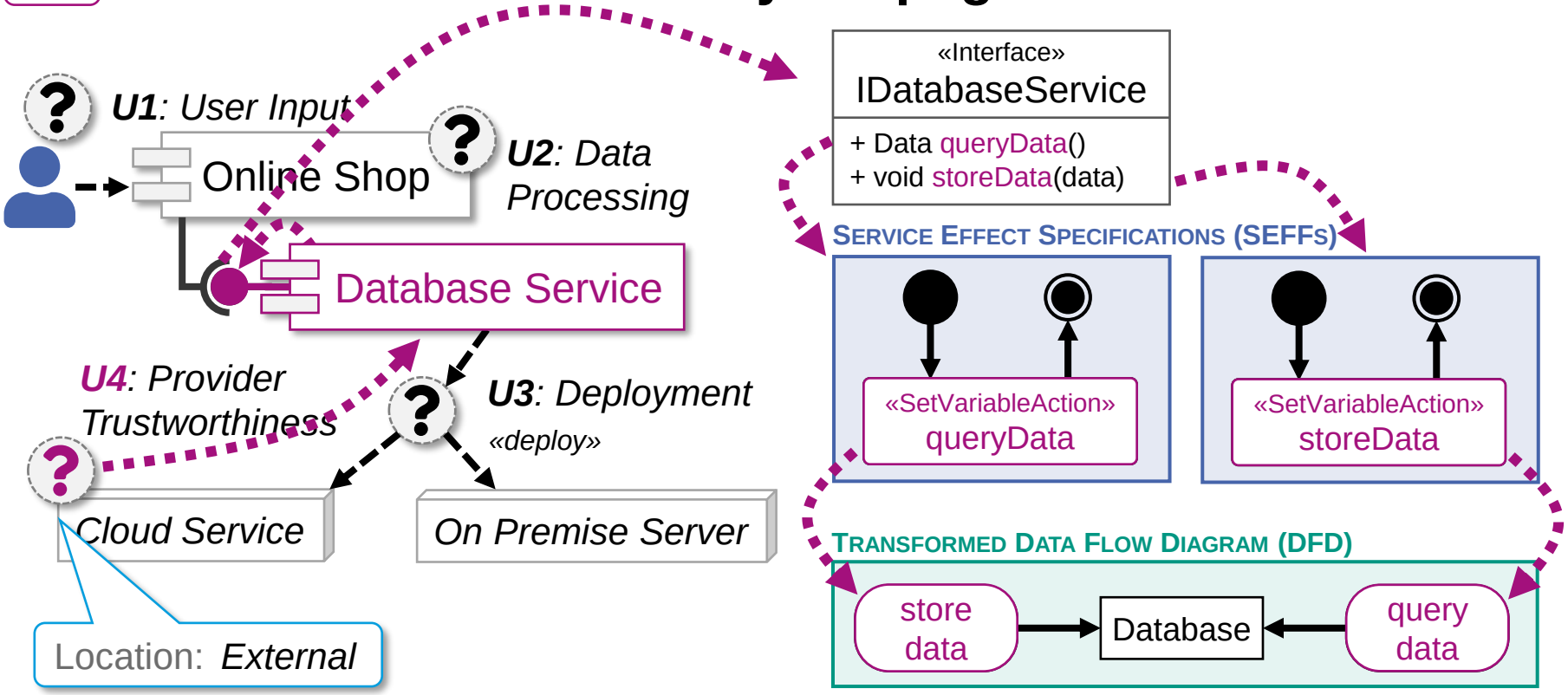
C2 Architectural Uncertainty Propagation



[17] R. Reussner et al., “Modeling and Simulating Software Architectures: The Palladio Approach”, The MIT Press, 2016.

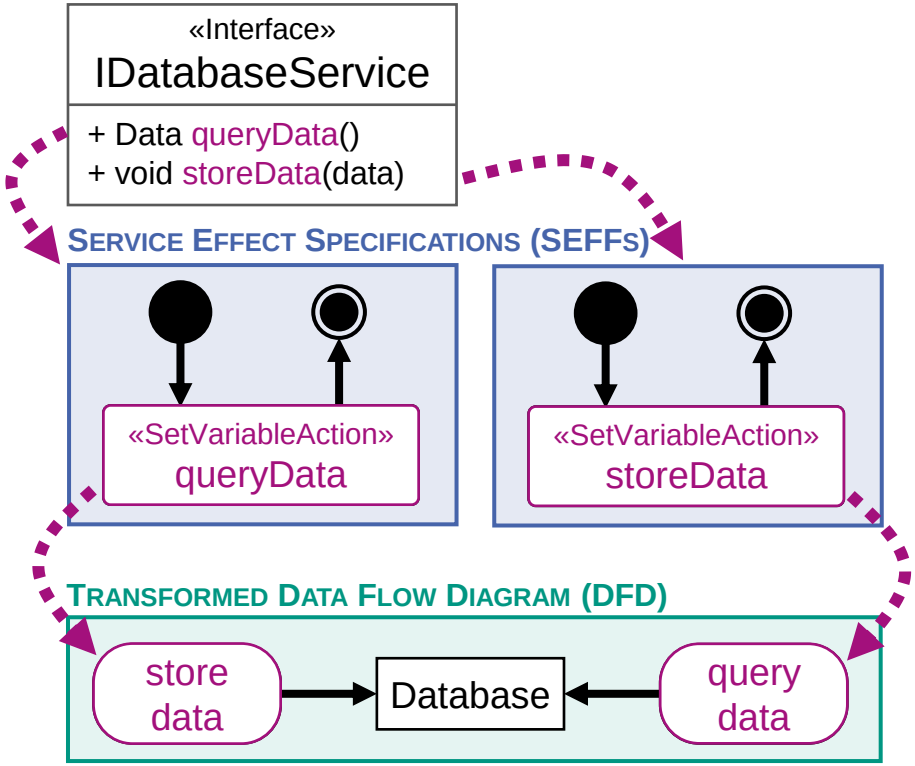
C2 Architectural Uncertainty Propagation



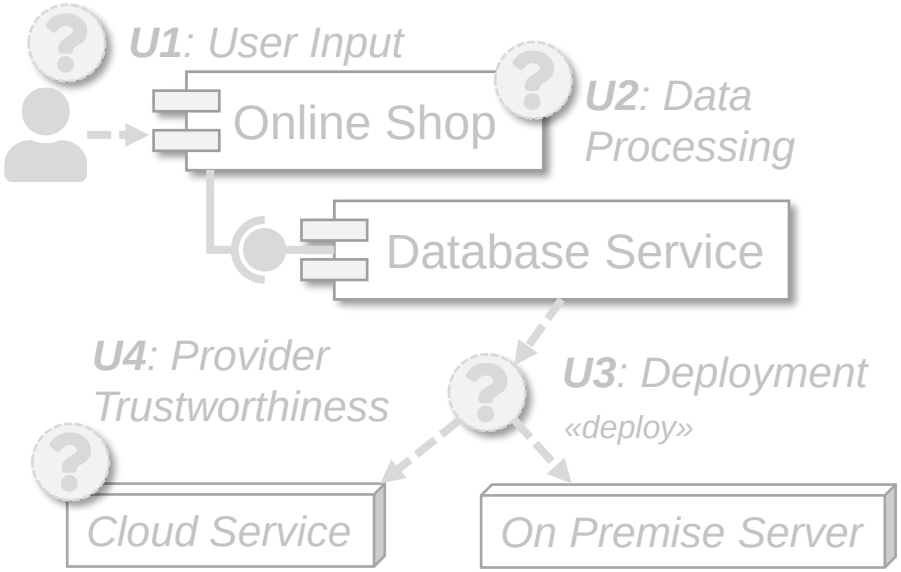
C2 Architectural Uncertainty Propagation

Algorithm for External Uncertainty Propagation

```
procedure PROPAGATEEXTERNALUNCERTAINTY(uncertainty, model)
  result ← ∅
  annotatedElement ← GETANNOTATEDELEMENT(uncertainty, model)
  switch TYPEOF(annotatedElement) do
    case UsageScenario
      actions ← GETACTIONS(annotatedElement, model)
      for action ∈ actions do
        if TYPEOF(action) = EntryLevelSystemCall then
          result ← result ∪ {action}
        end if
      end for
    case ResourceContainer
      allAssemblyContexts ← GETALLASSEMBLYCONTEXTS(model)
      for context ∈ allAssemblyContexts do
        if GETALLOCATION(context, model) = annotatedElement then
          component ← GETREPOSITORYCOMPONENT(context, model)
          seffs ← GETSEFFS(component, model)
          for seff ∈ seffs do
            actions ← GETACTIONS(seff, model)
            result ← result ∪ APPLYTOASSEMBLY(actions, context)
          end for
        end if
      end for
  return result
end procedure
```



C2 Uncertainty Impact Analysis



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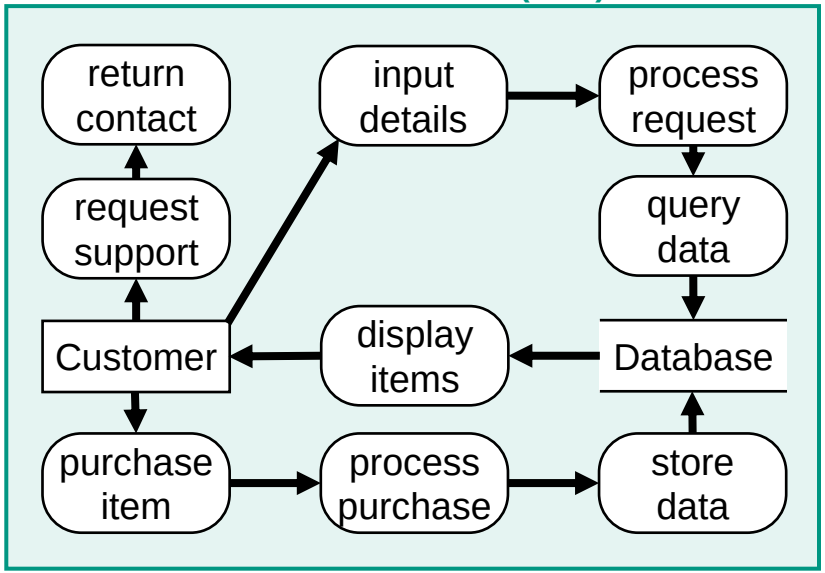
[7] S. Seifermann, et al., "Detecting violations of access control and information flow policies in data flow diagrams", JSS, vol. 184, Elsevier, 2022.

C2 Data Flow-Based Propagation

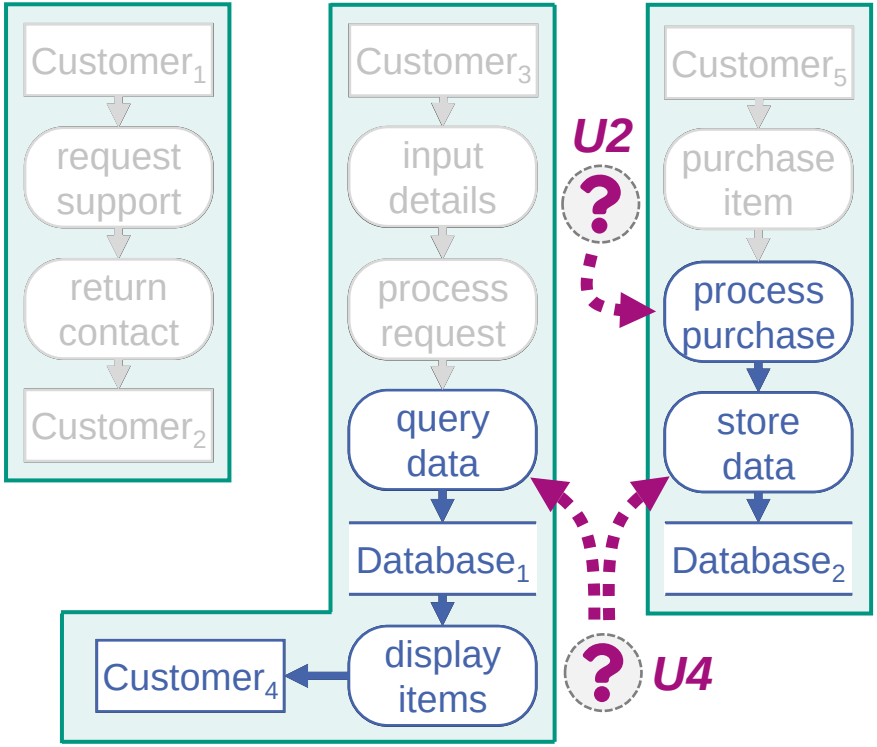
- Data flow diagrams can be represented as Directed Acyclic Graph (DAG) **G** = (**V**, **E**)
  - Data flows in a strict partial order **v' ≺ v"**
  - Split into Transpose Flow Graphs (TFGs)

TRANSFORMED DATA FLOW DIAGRAM (DFD)

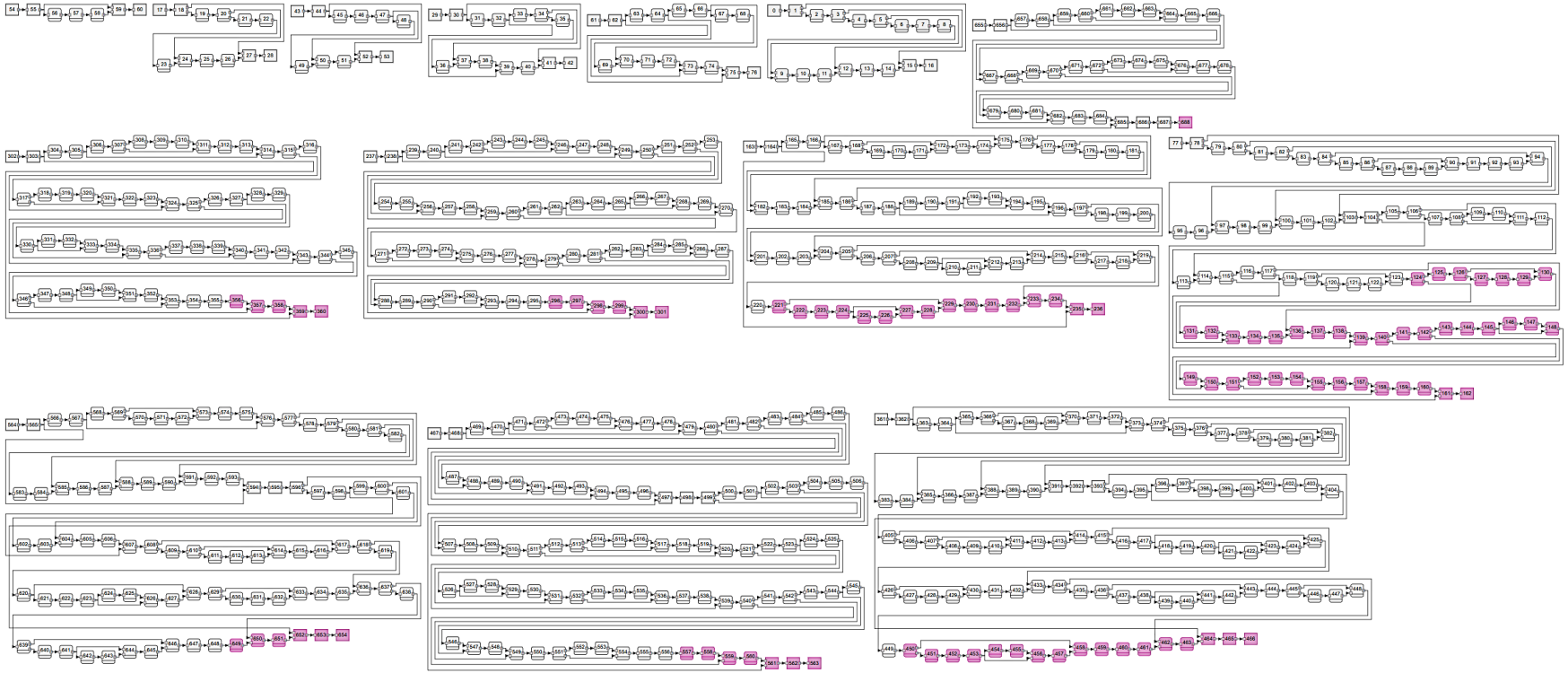


C2 Data Flow-Based Propagation

- Data flow diagrams can be represented as Directed Acyclic Graph (DAG) $G = (V, E)$
  - Data flows in a strict partial order $v' \prec v''$
  - Split into Transpose Flow Graphs (TFGs)
- We reuse the annotation function a, the architectural propagation p_A, and the mapping m from the architecture A
- The data flow-based propagation $p_D: V \rightarrow X \subseteq V$ yields an impact set, represented by an induced subgraph $G[X]$
- Uncertainty impacts follow the data flow: $\forall\, x \in X \subseteq V, \exists\, a \in A : m(a) = x \vee m(a) \prec x$
- The impact analysis of an uncertainty source S is a function $u : S \rightarrow X \subseteq V$, defined as $u = p_D \circ m \circ p_A \circ a$



Demonstration of Uncertainty Impact Sets

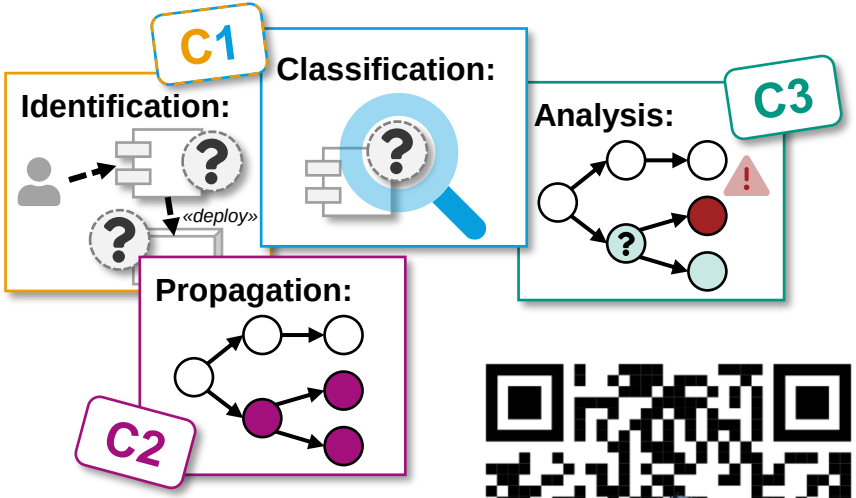


Conclusion

- **Foundation:** Data flow-based confidentiality analysis using the software's architecture
- **Goal:** Enabling to identify confidentiality violations with respect to uncertainty
- **Benefits:** Less expertise and less manual effort required, what-if analysis capabilities

Contributions:

- **C1: Identification** and **classification** of uncertainty regarding confidentiality
- **C2**: Architecture-based uncertainty **propagation** and impact analysis
- **C3**: Uncertainty-aware confidentiality **analysis** to identify violations



Dissertation, Tooling, Data

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