Composing Cross-Domain Solutions

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Dec 3rd, 2012
Motivation – The Big Picture

• Cross-domain solutions (CDSs) are integral components of the U.S. Defense Department’s global information grid (GIG)
• CDSs provide assured information sharing, **BUT**

• CDSs have **limitations**
  – Not particularly suitable for net-centric operations
  – Exhibit large deployment times which cannot cope with stringent requirements
Agile CDS Vision

• **Decomposing** the problem into sub-problems that are more **tractable**
• Then **integrating** the component solutions

• The building blocks for achieving this:
  – Formal specifications for generic downgrading engines
  – Formal languages for data sanitization rules
  – Filters for specific data types
  – Attribute-based access control

• Using **pre-certified commercial off-the-shelf** (COTS) CDS facilitates rapid deployment in the field
  – The availability of COTS devices depends on their timely evaluation
Problem to Solve

Speed-up CDS Evaluation
Data Downgrading

- High-assurance CDSs are instrumental for information sharing across security domains

- A system’s security-critical components are decomposed into modules that can each be completely verified (MILS)

- Downgraders need to cope with multiple types of data, requiring transformation and sanitization mechanisms to allow the information flow
Decomposing Sanitization

• Address the problem of downgrading data that has components with multiple classification levels by leveraging
  – The nature of the data being downgraded
  – The available trusted computing infrastructure

  to decompose the downgrading functionality to the point that each module can economically be formally specified and have its operational behavior verified

• Make complex data sanitization practical
  – Inspired by multiple independent levels of security (MILS)
Architectures for Composing Cross Domain Solutions

- **Intra-CDS**
  - High
  - CDS
  - Sanitizer
  - Sanitizer
  - Low

- **Serial CDS**
  - High
  - CDS
  - Intermediate
  - CDS
  - Low

- **Parallel CDS**
  - High
  - CDS
  - CDS
  - *Low*
Sanitization Algorithms

• Previously studied in the context of publishing privacy-sensitive data
  – To preserve the privacy of individual record owners, a downgrader sanitizes information derived from such databases

• Different methods have been approached
  – Perturbing the query inputs and outputs, and restricting the number of queries
  – Suppression that removes records from the sanitized output
  – Randomization that adds noise to perturb the data, and multi-views that provide sanitization through diverse perspectives.

• For CDS, the data may never have been observed previously
  – Recent research on streaming differential privacy provides a framework for designing sanitization algorithms appropriate for a CDS
Sanitizers / CDS Characteristics

- Operate on a stream of items
- Inspect each item and update internal state
- Produce an output either for each item or at the end of the stream
Differential Privacy for Data Streams

• **Privacy against continual output observation**
  – The adversary examines the output all the time

• **Pan-Privacy**
  – The adversary examines also the internal state (intrusion)
    • Announced (subpoena)
    • Unannounced
      – Once? Several times? All the time?
Characterizing Leakage of Information

• Leakage may depend on auxiliary information available externally, but never observed by the downgrader

• **User-level X-adjacency**
  – Data streams $S$ and $S'$ are **X-adjacent** if they differ only in the presence or absence of *any number* of occurrences of a single item $x \in X$

  $S = axbxcxdxxxex$
  $S' = abcdxe$

• **Event-level X-adjacency**
  – Data streams $S$ and $S'$ are **X-adjacent** if the number of instances of one item replaced by another is *at most* 1

  $S = abcdexfg$
  $S' = abcdeyfg$
Differential Privacy Against Continual Observation

- **Assumption**: The sanitizer / CDS is trusted

- A - algorithm working on a stream of data

- A is **ε-differentially private** against continual observation if for all
  - adjacent data streams S and S’ (user or event level)
  - outputs \( \sigma_1 \sigma_2 \ldots \sigma_t \)

\[
e^{-\epsilon} \leq \frac{Pr[A(S)] = \sigma_1\sigma_2\ldots\sigma_t}{Pr[A(S')] = \sigma_1\sigma_2\ldots\sigma_t} \leq e^\epsilon
\]
Pan-Privacy ("inside and out")

- **Assumption**: The sanitizer / CDS is not trusted

- A - algorithm working on a stream of data
- I - the set of internal states of the algorithm
- σ - the set of possible output sequences

- A mapping stream items to I×σ is (ε-differentially) pan-private (against a single unannounced intrusion) if for all
  - adjacent data streams S and S' (user or event level)
  - I' ⊆ I and σ' ⊆ σ

\[
e^{-\epsilon} \leq \frac{Pr[A(S) \in (I', \sigma')]}{Pr[A(S') \in (I', \sigma')]} \leq e^\epsilon
\]
Composable Sanitization

- **Theorem** The composition of an $\varepsilon_1$-differentially private mechanism and an $\varepsilon_2$-differentially private mechanism is at worst $(\varepsilon_1 + \varepsilon_2)$-differentially private.

\[
\sum \varepsilon_i \text{- differentially private CDS}
\]
Conclusions

• High-assurance systems with multiple security levels use data filters to facilitate the safe flow of information

• As the content and context of the data increases in complexity, the cost and time to certify CDS is growing rapidly

• Downgrading functionality should be decomposed to the point where each filter provides a streaming differential privacy guarantee and its certification is economically viable

• The resulting filters can be combined to provide equivalent functionality to that provided by monolithic downgraders
Acknowledgments

- This material is based upon work supported by the National Science Foundation under Grant IIS-1116414. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.
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