Towards Graph Watermarks

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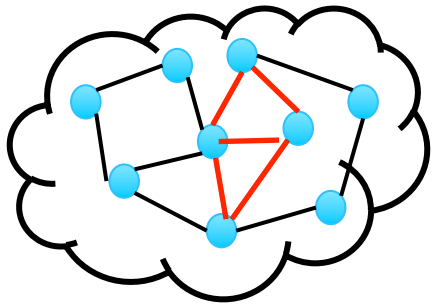
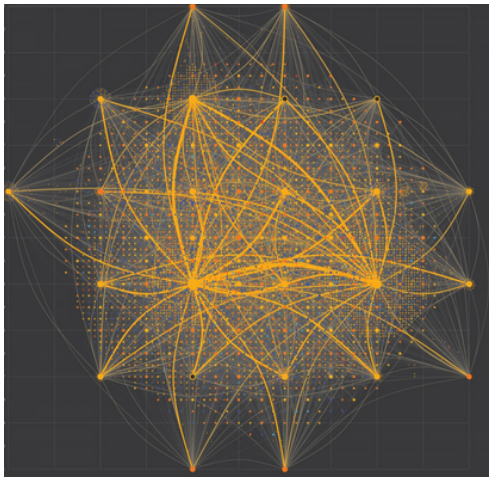
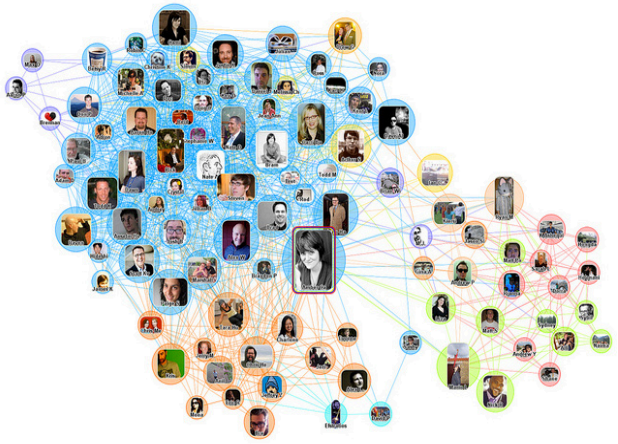
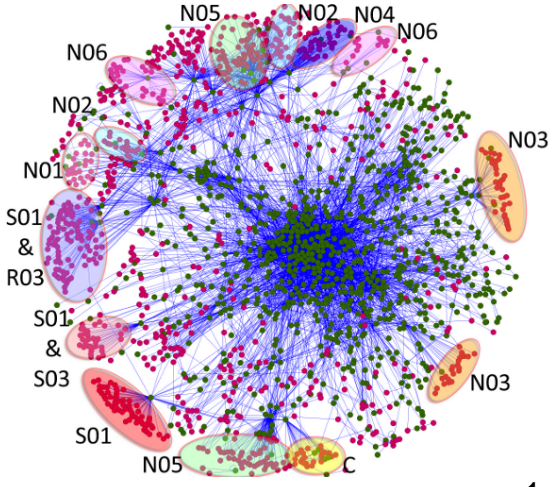


Sensitive Datasets Captured in Graphs

- Graphs are everywhere
  - e.g. Internet networks, Social networks, Biological networks
- Many of today's ***sensitive*** datasets are captured in large graphs
  - e.g. maps of autonomous system, friendships in social networks, interaction of proteins in personal health care



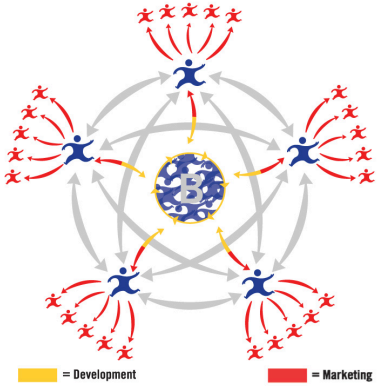




Desires to Securely Share Graphs

- Data owners: often want to share data with selected parties, without data leakage into public domain
  - ISP vs networking equipment vendor
  - Facebook vs trusted academic collaborators

- Research community: need real graphs for progress in many areas
  - Understand underlying structure and process
  - Validate models and theories



Current Solutions: Far From Ideal

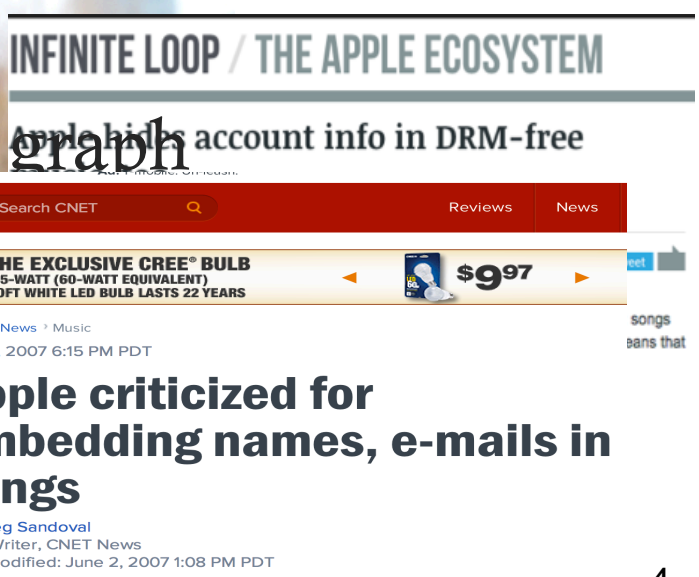
- Option 1: Build strong access control mechanisms
  - Have limited control once the data is shared
  - Attacks on human elements
    - e.g., phishing, baiting

- Option 2: modify data to reduce the impact of potential leakages
  - Usually significant modification, make data noisy
    - Subsampling, summarization, synthetic graphs
  - Significantly reduces "utility" of graph dataset

A new alternative: graph watermarks

Watermark: Data Signature

- Watermark: ***signature*** in data as ownership identifier
  - Data owner embeds a signature in the data
  - If the data is leaked, announce ownership by the signature
- Widely used in digital files to limit piracy
- ***Graph watermark***: signature in a graph
  - Watermarks applied to graphs
  - Serve as a deterrent against grap


INFINITE LOOP / THE APPLE ECOSYSTEM

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June 1, 2007 6:15 PM PDT

Apple criticized for embedding names, e-mails in songs

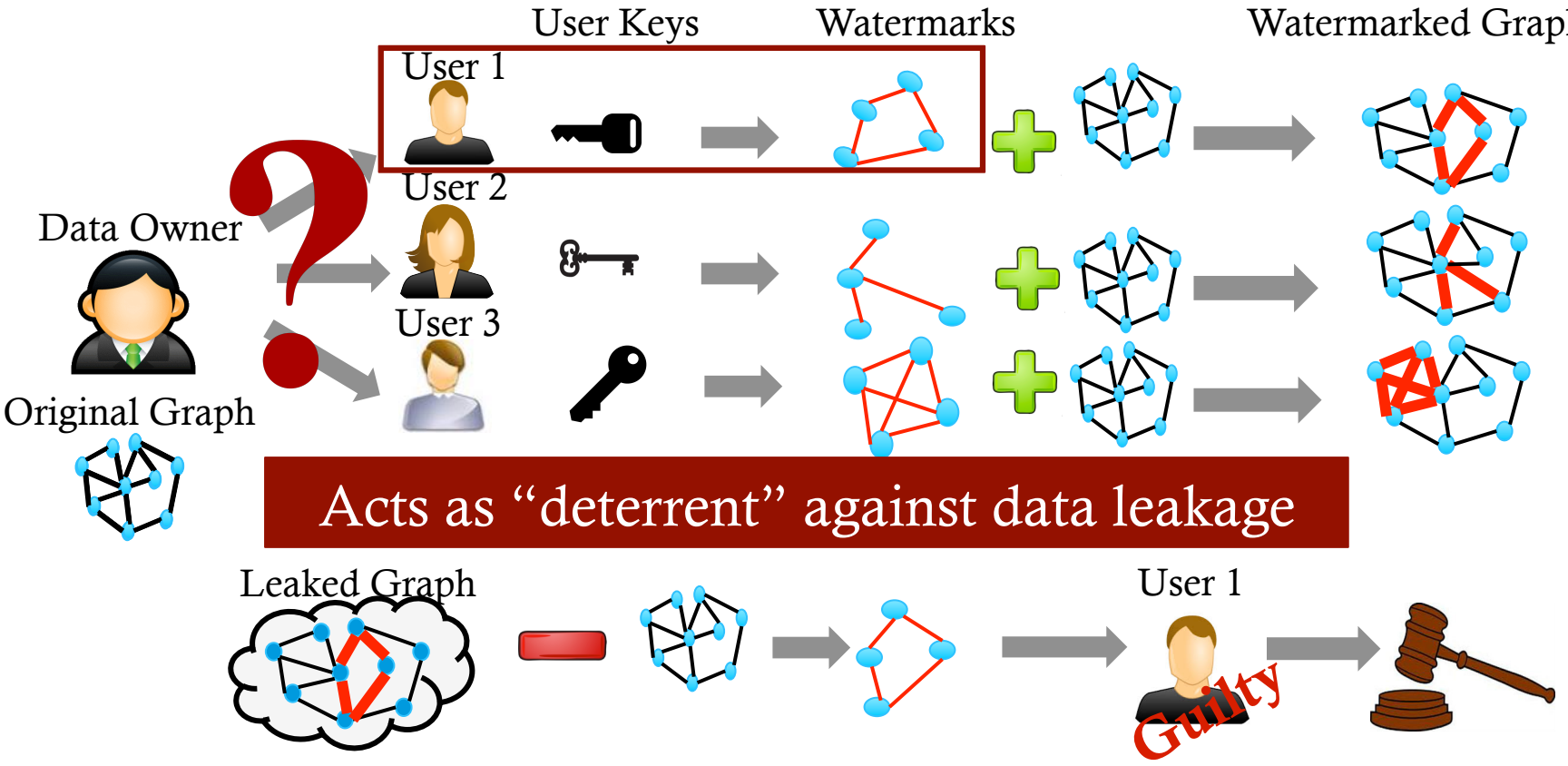
By Greg Sandoval
Staff Writer, CNET News
Last modified: June 2, 2007 1:08 PM PDT

Our Goals

- Design an ***effective*** graph watermark system
  - **Low distortion**
    - Small impact on graph structure
    - Difficult to detect
  - **Uniqueness**
    - Not occur naturally nor easily faked
    - Existence securely associated with an authorized party
  - **High robustness**
    - Watermarks remain after attacks
  - **Efficient** to embed and extract watermarks

Scenario: Share Graph With Multiple Users

- Each user uniquely associated with a watermark
- Once find a leaked version, identify the source by watermark



Outline

- Motivation
- Graph Watermark System
  - Watermark Embedding
  - Watermark Extraction
- Key Properties
- Experimental Evaluation Summary
- Conclusion

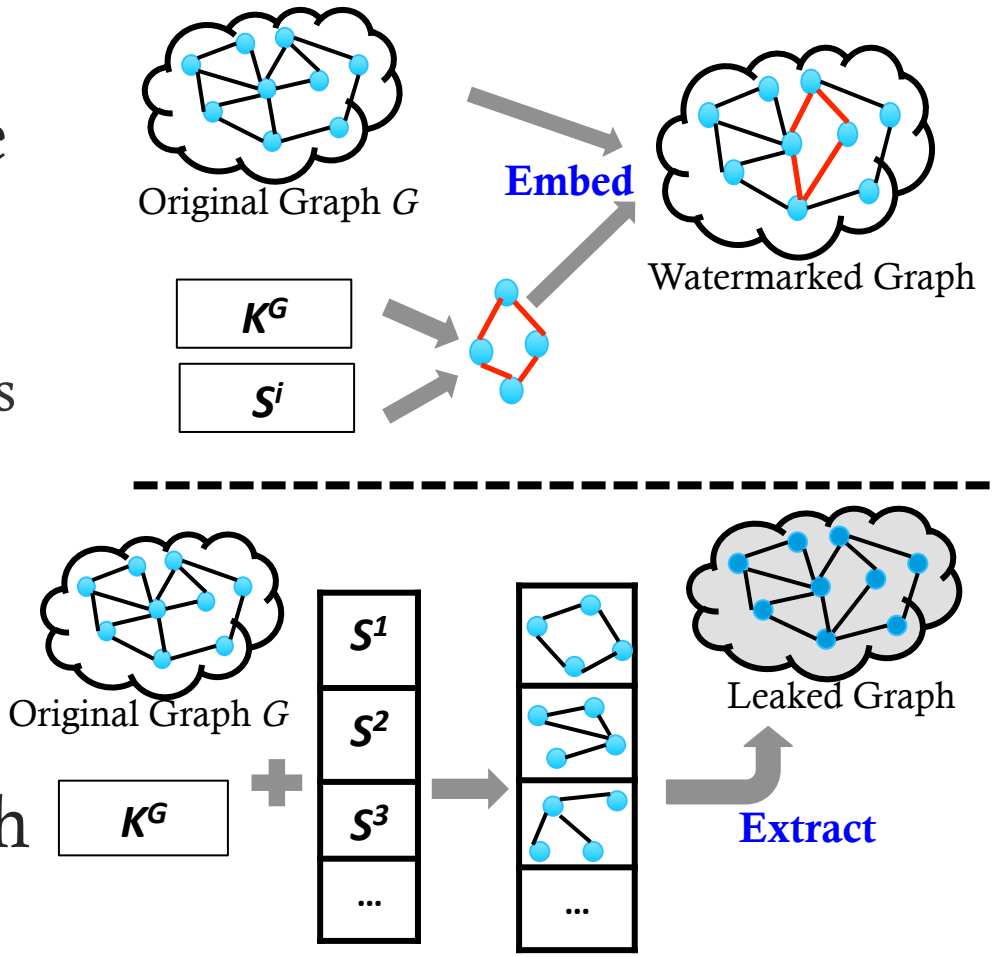
Graph Watermark System Overview

- **Embedding**:

  add watermark into the original graph
  - Generate watermark with G's secret key K^G + user i's signature S^i
  - Require joint efforts from data owner and user i

- **Extraction**:

  search in a leaked graph for any watermark



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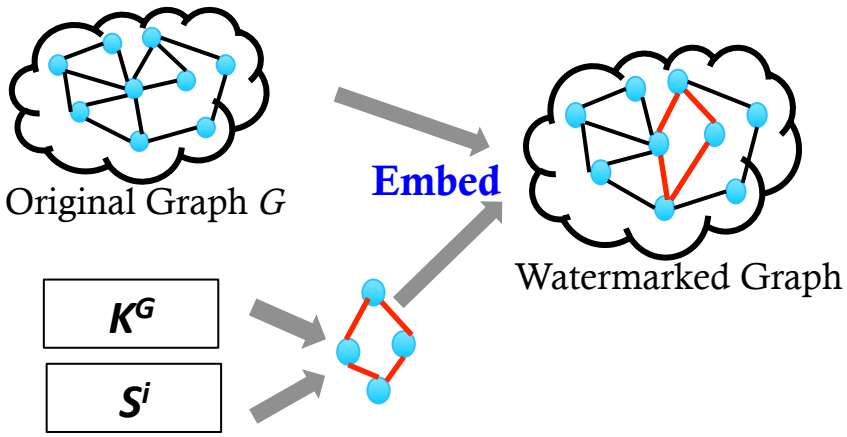
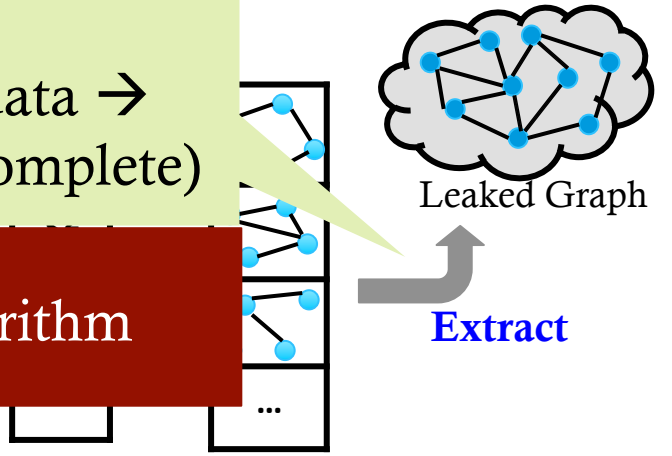


Challenges:
Rely on only ***graph structure***, not meta data →
Subgraph isomorphism problem (NP-complete)

- [illegible]

Our Solution: Efficient Pruning Algorithm

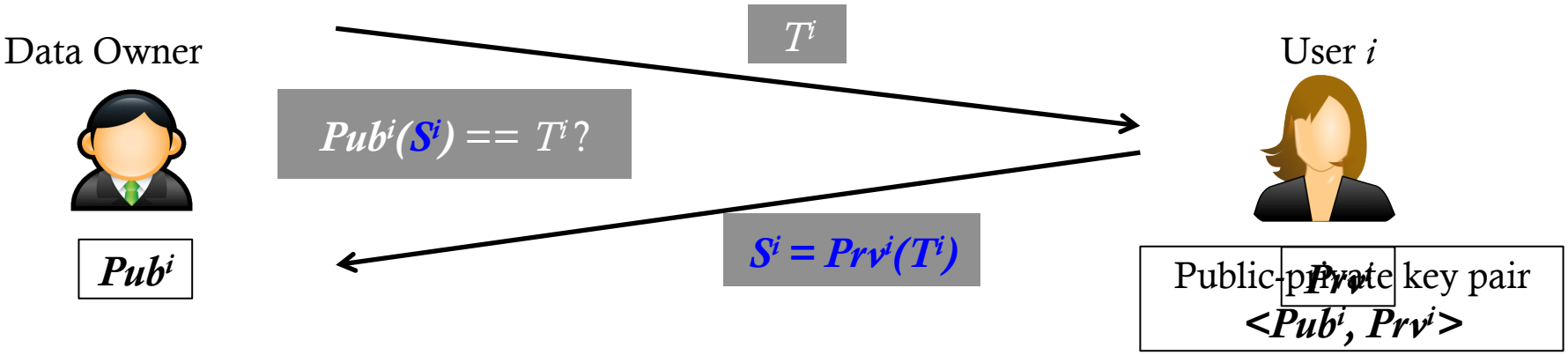
for any watermark



Watermarking Embedding

Step 1: verify user *i*'s signature S^i

- A random generator seed $\Omega^i = K^G + S^i$



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Step 1: verify user *i*'s signature S^i

- A random generator seed $\Omega^i = K^G + S^i$

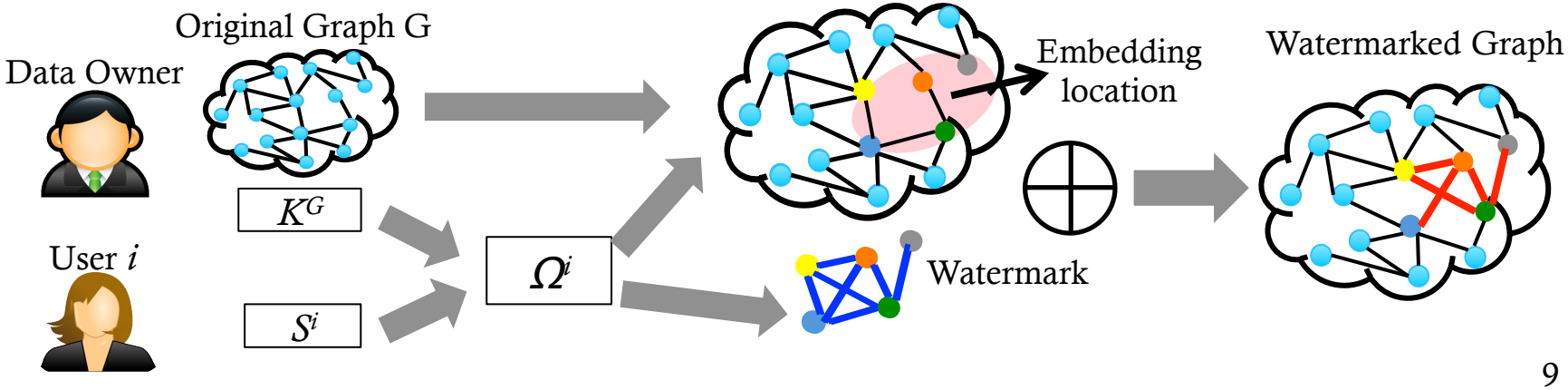
Step 2: generate the watermark

- A random graph of *k* ordered nodes, seeded by Ω^i

Step 3: select embedding location

- *A subgraph of k* ordered nodes in G, seeded by Ω^i

Step 4: embed the watermark (XOR)



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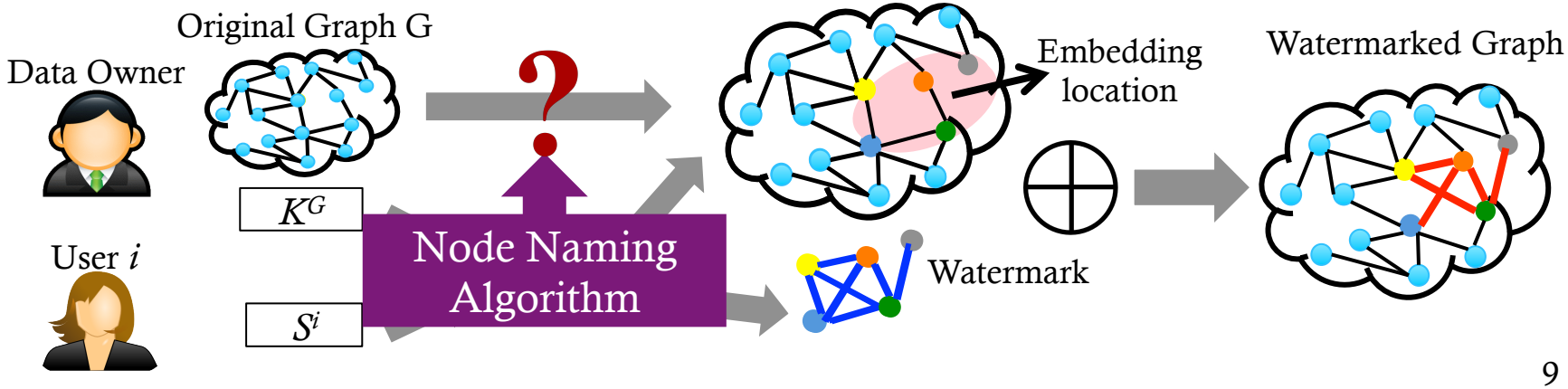
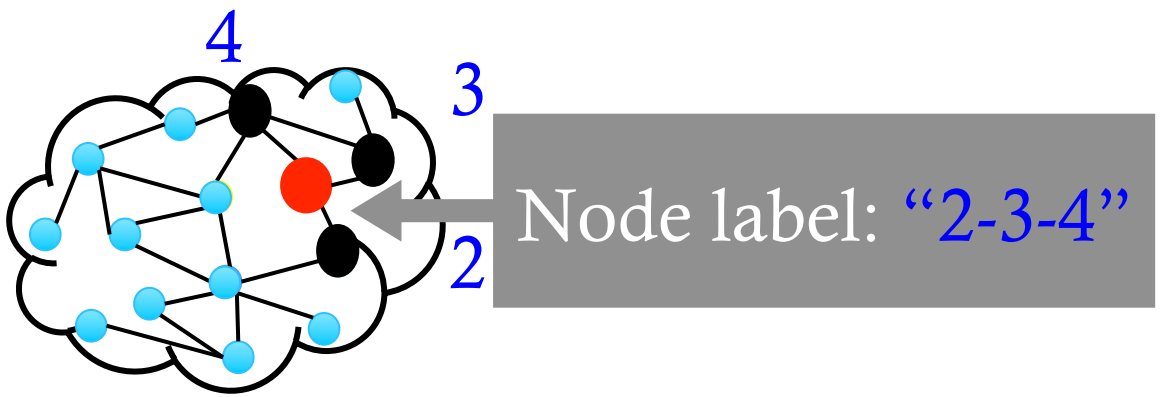


Node Naming Algorithm

- Generate "label" for nodes
  - Regenerate "meta data" from only graph structure
  - Label = an array of sorted neighboring degrees

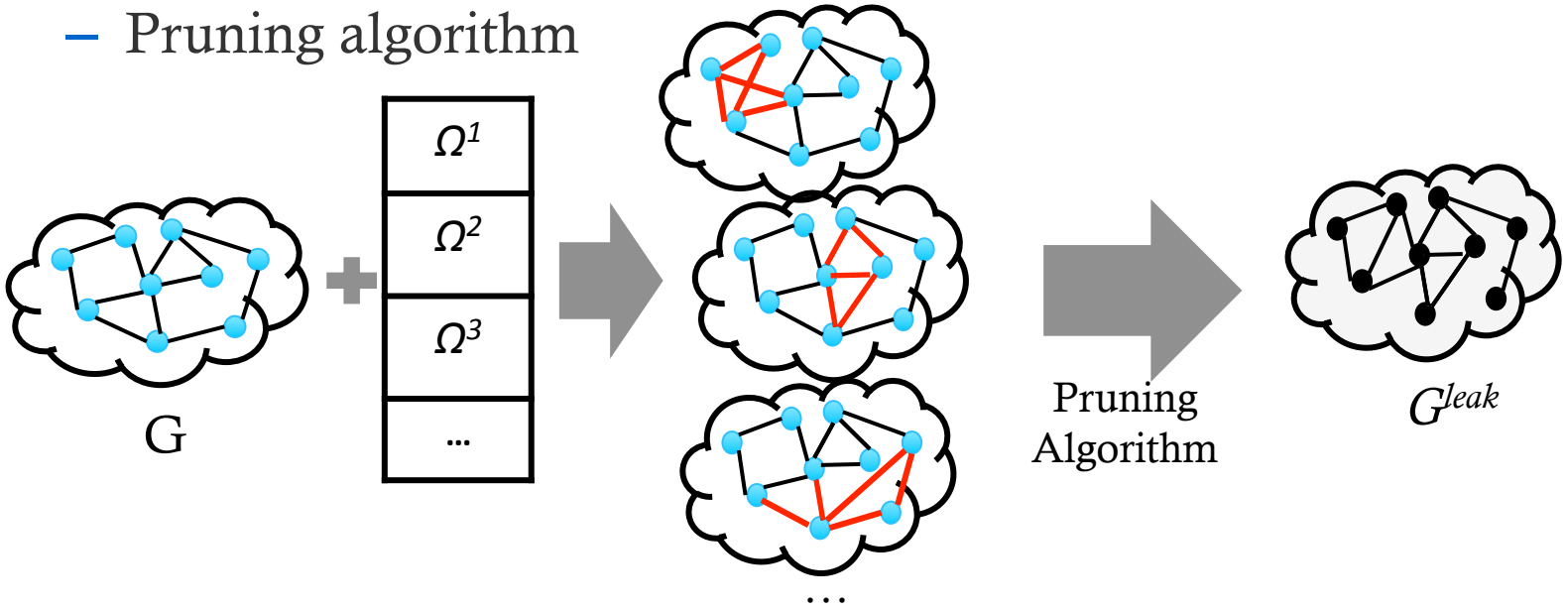


- Efficient in practice
  - Real graphs often have high node heterogeneity
  - Small # of nodes share the same label

Watermark Extraction

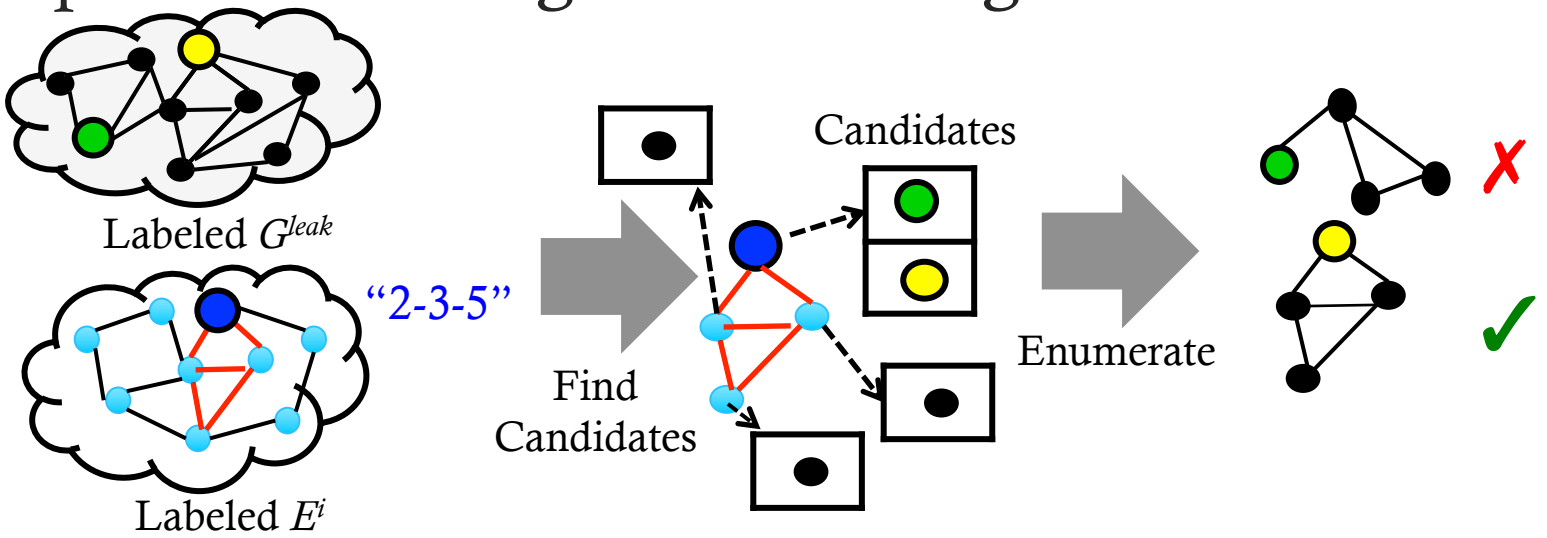
Data owner: a leaked graph G^{leak}, original graph G, random generator seed Ω^i for each user (i=1,2,…)

- **Step 1**: regenerate embedded watermark
  - Repeat watermark embedding for each user
- **Step 2**: search if any embedded watermark in G^{leak}
  - Pruning algorithm



Pruning Algorithm

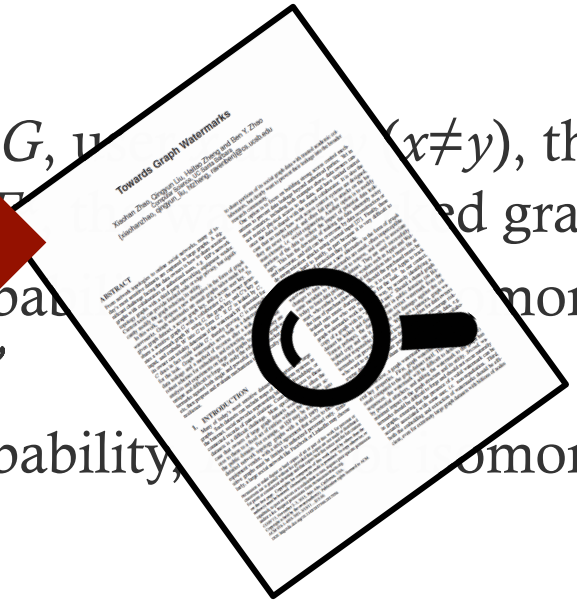
- Exhaustive search
  - Efficient by restricting to small # of nodes
- For each embedded watermark E^i (i=1,2,…)
  - Find candidates in G^{leak} by matching node label
  - Enumerate combinations and check graph structure
- Stop until matching or exhausting all combinations



Watermark Uniqueness

- Watermark uniqueness: an embedded watermark ***not*** isomorphic to
  - Any subgraph of the original graph *(naturally occurring)*
  - Any other embedded watermarks *(watermark collision)*
- Proof sketch
  - Given original graph G, u… ($x \neq y$), the embedded watermark o… …d graph of user y G_y'
  - Step 1: with high pr…bat… …morphic to ***a given*** subgraph in G *nor* G_y'
  - Step 2: with high probability, … …omorphic to ***any*** subgraph in G *nor* G_y'

Details



Watermark Applicability

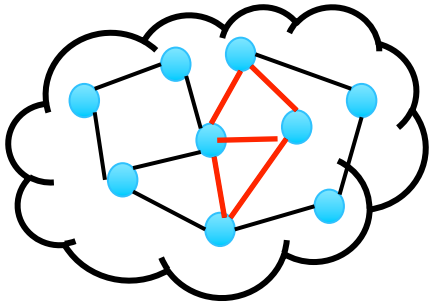
- Graphs suitable for watermarking
  - Can "well hide" embedded watermark
  - Judging criteria
    - Node degree
    - Subgraph density
- Test on 48 real network graphs
  - Represent 10 types of networks
    - e.g. OSNs (Facebook, Youtube …), communication networks
  - Sizes: thousands to millions nodes/edges
- Most (35) graphs are suitable
  - Unsuitable: only 3 types
    - e.g. Road networks
  - Sparse graphs

Experimental Evaluation Summary

- Low distortion
  - Node/edge modification < 0.04%
- High efficiency
  - e.g. graph with 2M nodes, 16M edges
    - Embedding: < 2 mins
    - Extraction: < 4 mins when parallelized across 10 machines
- Robust to attacks
  - Single attack model: have ***one*** watermarked graph
  - Collusion attack model: have ***multiple*** watermarked graphs
  - Multiple defense techniques (details in paper)

Conclusion

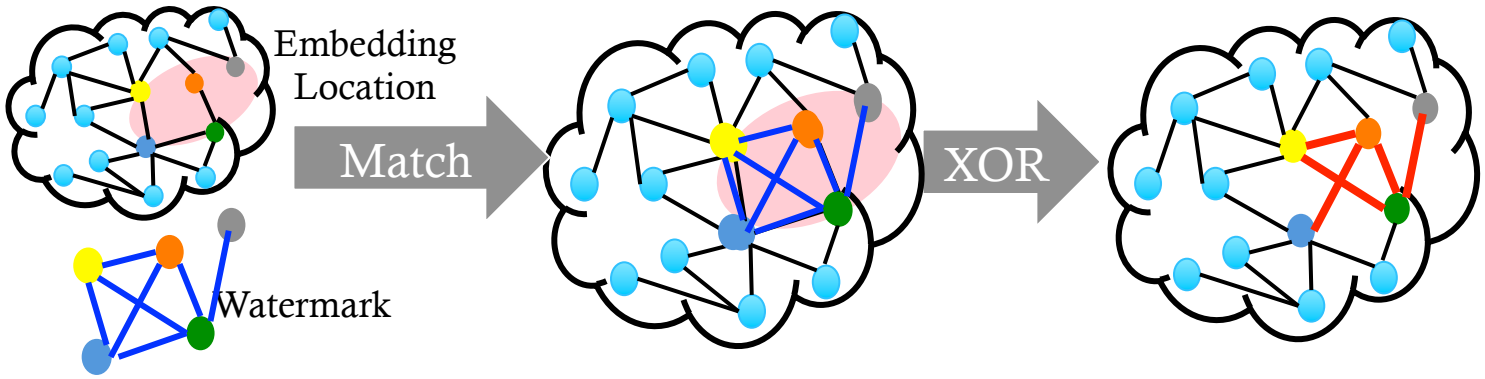
- Graph watermarks useful in many application
  - e.g. tracking data leaks, data authentication
- Our work: a first step
  - Identify the problem
  - Initial implementation: an ***efficient*** system with ***unique***, ***robust*** watermarked graphs in ***low distortion***
- Future work: improve robustness against many other attacks



Thank you
Any questions?

Watermark Embedding

- Select embedding location
  - Sort node labels of G
    - e.g. use secure one-way hash like SHA-1
  - Use Ω^i to randomly pick labels as selected nodes
    - If multiple nodes have the same labels, sort them in any deterministic order and use Ω^i to pick one
- Embed watermark
  - Match both subgraphs by node order
  - Apply XOR on each pair of nodes



Fast Pruning Algorithm

- Complexity is bounded: $O\left(\sum_{m=2}^{k}\left(\prod_{i=1}^{m}|C_i|\right)\cdot\frac{1}{2}^{\binom{m}{2}}\right)$
  - $|C_i|$: # of candidates for i-th node in embedded watermark
- In practice, far from the worst case scenarios
  - Real graphs have high node heterogeneity → small $|C_i|$
- Repeated empirical experiments show efficiency

Graph	# of Nodes	# of Edges	Embedding	Extraction*
Facebook (LA)	603,834	7,676,486	< 1min	< 1min
Flicker	1,715,255	15,555,041	< 2min	< 4min

*: Extraction parallelized across 10 machines, each with 192 GB RAM

Watermark Uniqueness

- Intuition: embedded watermark is a special graph, when large enough difficult to find isomorphism in G
  - Erdos-Renyi random graph with edge probability ½
  - Size $k \geq (2+\delta) \log_2 n$
    - n: size of G, $\delta > 0$
- We prove when $k \geq (2+\delta) \log_2 n$
  - Prob. of embedded watermark isomorphic to any subgraph in G

$$P < \frac{1}{2}^{\frac{\delta k^2}{2(2+\delta)} - \frac{3k}{2} + 1}$$

  - Reduces exponentially to *0* as k increases
    - e.g., for G with 5M nodes, $k = 52$, $P < 10^{-30}$

Watermark Applicability

- 48 real graphs: 35 suitable

OSNs	✓	Collaboration networks	✓
Citation Networks	✓	Communication networks	✓
Web graphs	✓	Location based OSNs	✓
AS graphs	✓	Amazon Co-purchasing Networks	✗
P2P networks	✗	Road Networks	✗

- Judging criteria for a suitable graph G
  - Have expected ***node degree*** for embedded watermark between
    - [min degree in G, max degree in G]
  - Have expected ***graph density*** for embedded watermark
    - [min density in k-size subgraph in G, max density in k-size subgraph in G]

Attack Models

- Single Attack: have ***one*** watermarked graph
  - Best strategy: randomly adding or deleting edges
  - Defense: additional features in system
    - e.g. add randomness in node labeling and matching, embed a watermark multiple times
- Collusion Attack: have ***multiple*** watermarked graphs
  - Best strategy: compare graphs to remove watermarks
  - Defense: hierarchical watermark embedding
    - Embed watermarks with potions of overlap

Hierarchical Embedding