Predictive Mitigation of Timing Channels in Interactive Systems

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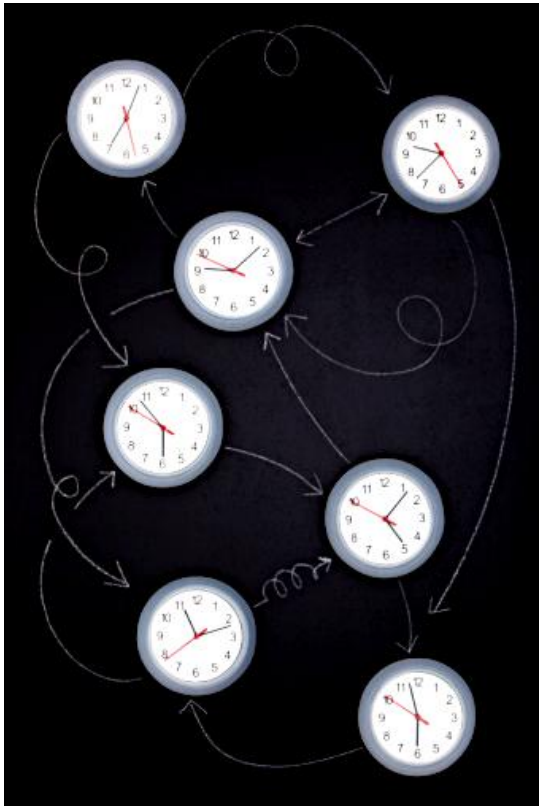
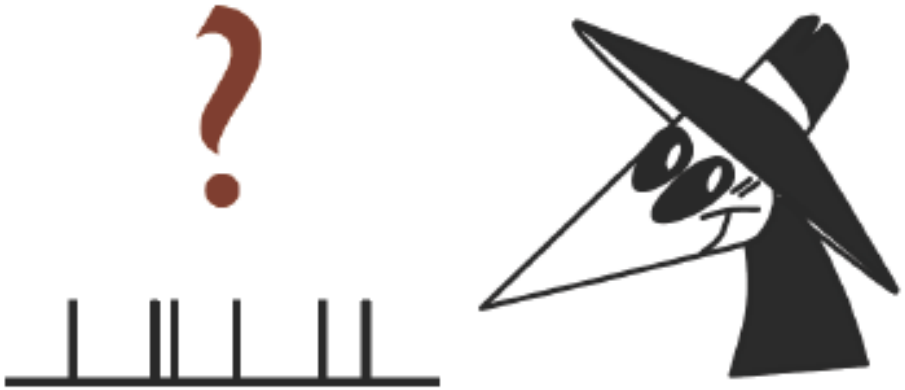
Timing Channels





Hard to detect and prevent

Timing Channels: Examples

- Cryptographic timing attacks [Kocher 96, Brumley&Boneh 05, Osvik et. al. 06]
  - RSA, AES keys are leaked by decryption time
- Cross-site timing attacks [Bortz&Boneh 07]
  - Load time of a web-page reveals login status, as well as the size and contents of shopping cart
- Use as covert channels [Meer&Slaviero 07]
  - Transmit confidential data by controlling response time, e.g., combined with SQL injection
- **Timing channels are big threats to security!**

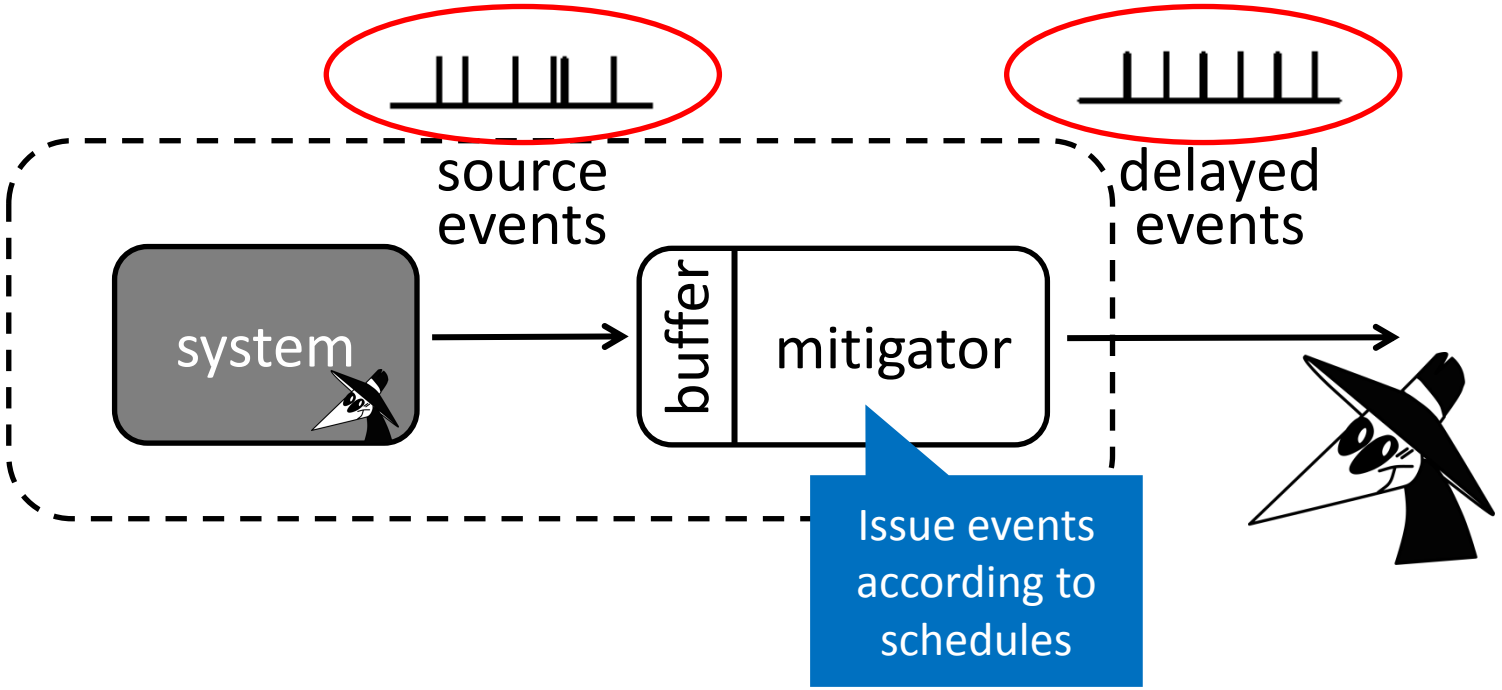
Timing Channel Mitigation

- Limitations of known approaches
  - Delay to the worst-case execution time – bad performance
  - Add random delays – linear leakage
  - Input blinding – specialized to cryptography
- Our solution:
  - Asymptotically logarithmic leakage
  - Effective in practice
  - Applies to general computation

Outline

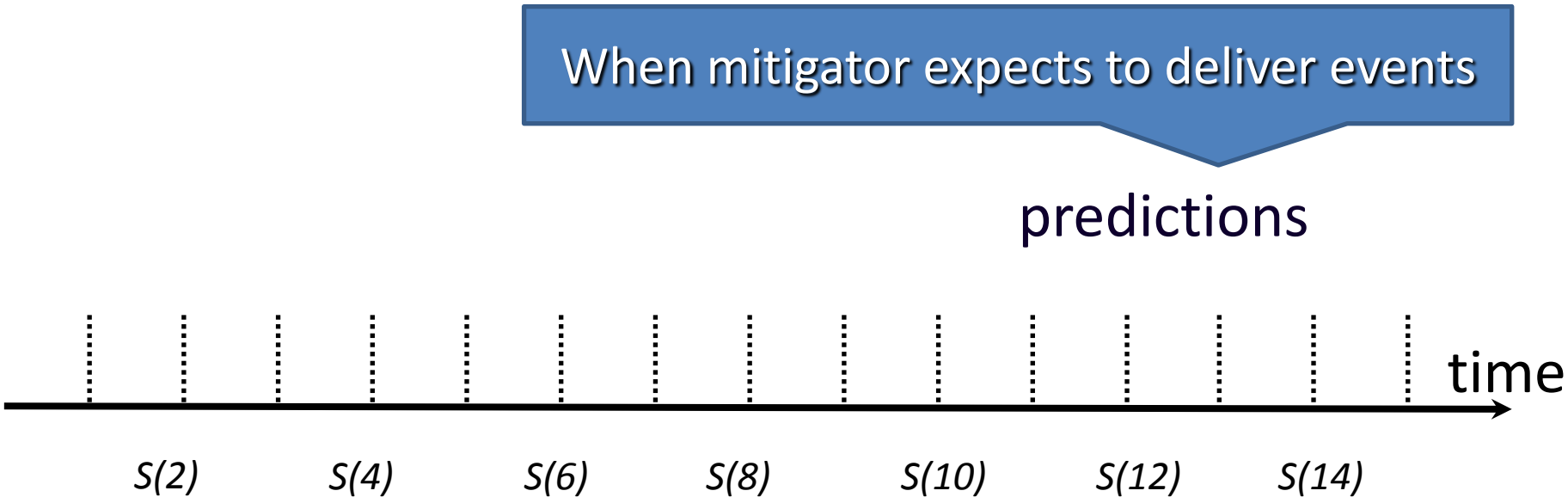
- Background on predictive black-box mitigation (CCS'10)
- Predictive mitigation for interactive systems (e.g., web services)
  - Prediction with public information
  - Generalized penalty policy & leakage analysis
  - Composition of mitigators
- Evaluation

Background: Predictive Black-Box Mitigation of Timing Channels (CCS'10)



Strong attacker model: timing of source events may be controlled

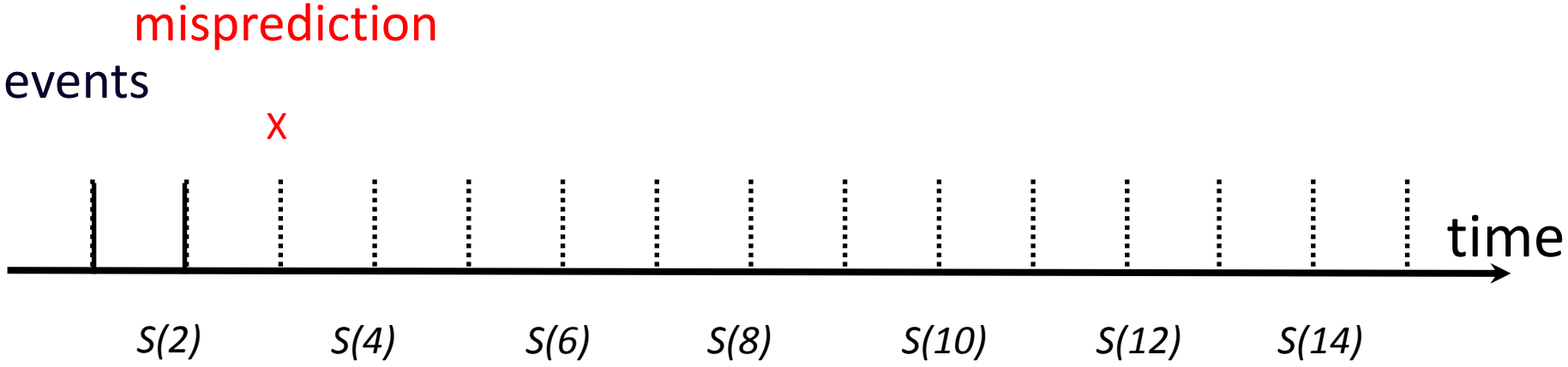
Example: Doubling



Mitigator starts with a fixed schedule *S*

S(i) – prediction for *i*-th event

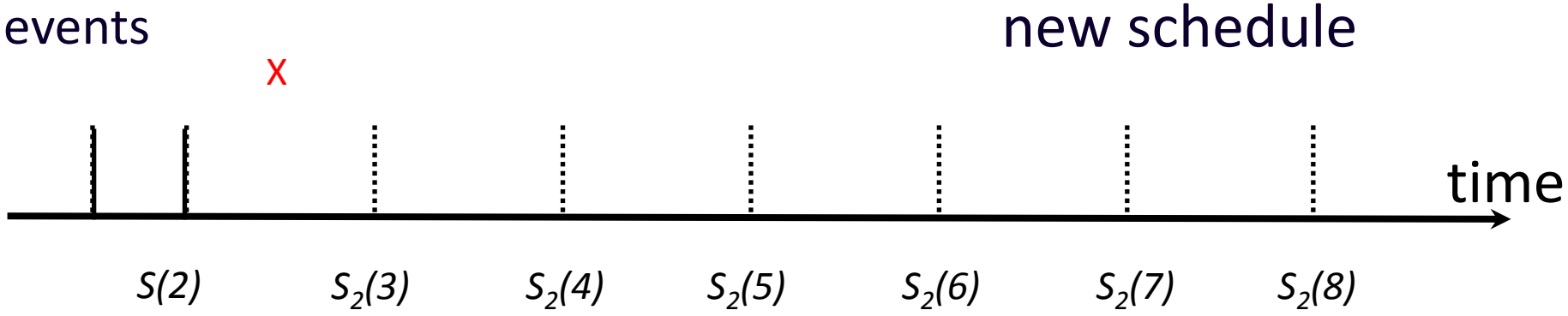
Example: Doubling



When event comes before or at the prediction – delay the event

little information leaked

Example: Doubling

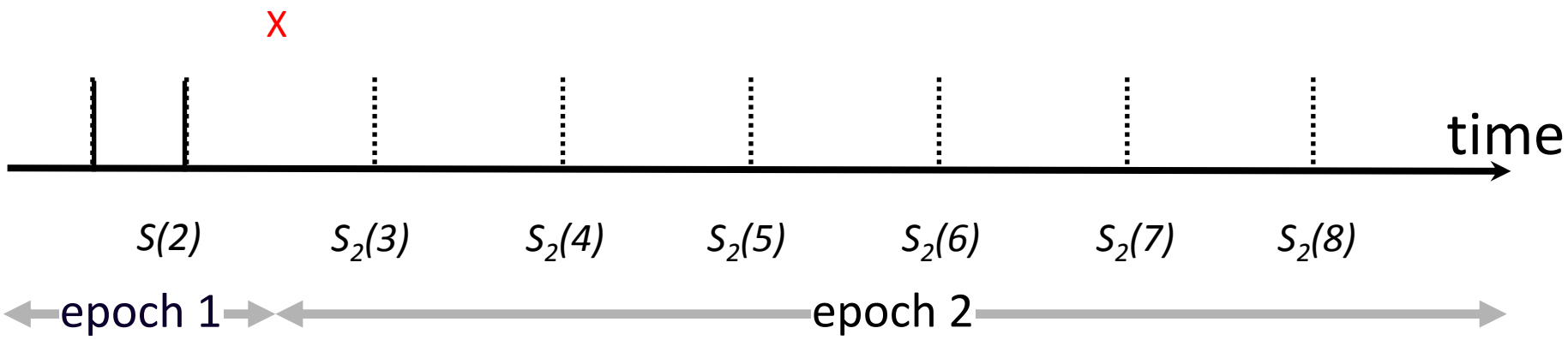


Adversary observes mispredictions **information leaked!**

New fixed schedule S_2 **penalizes** the event source

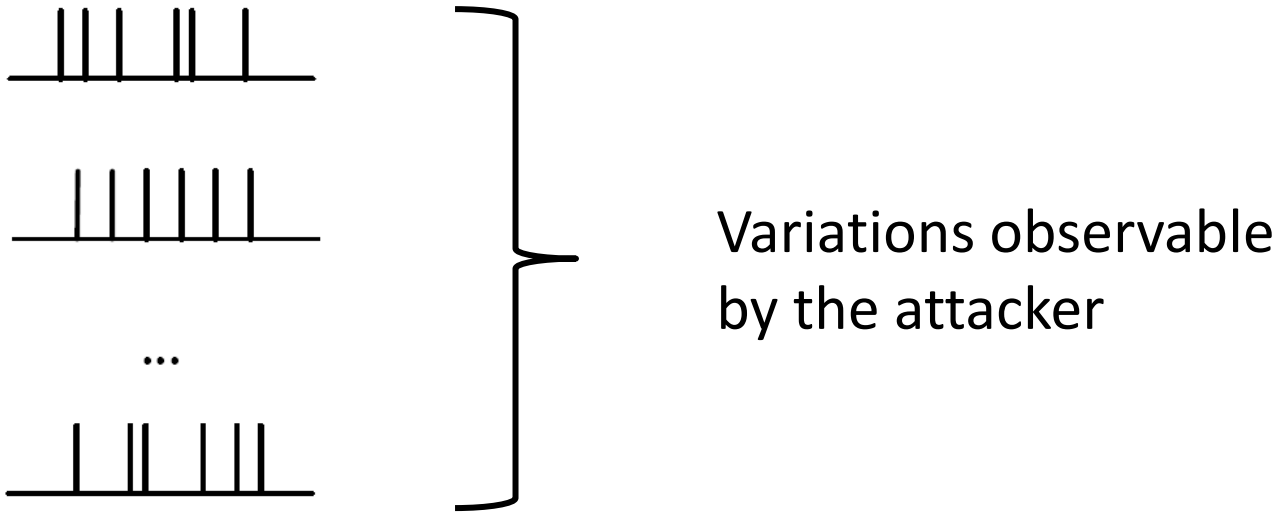
Example: Doubling

Epoch: period of time during which mitigator meets all predictions



Little information leaked in each epoch

Leakage & Variations



- Leakage measurement (log of # timing variations)
  - Also bounds
    - mutual information (Shannon entropy)
    - min-entropy

Important Features

- Information leaks via ***mispredictions***!
- General class of timing mitigators
  - Doubling scheme

$$\text{Leakage} \leq O(\log^2 T) \text{ bits}$$

  - Adaptive transitions
  - …

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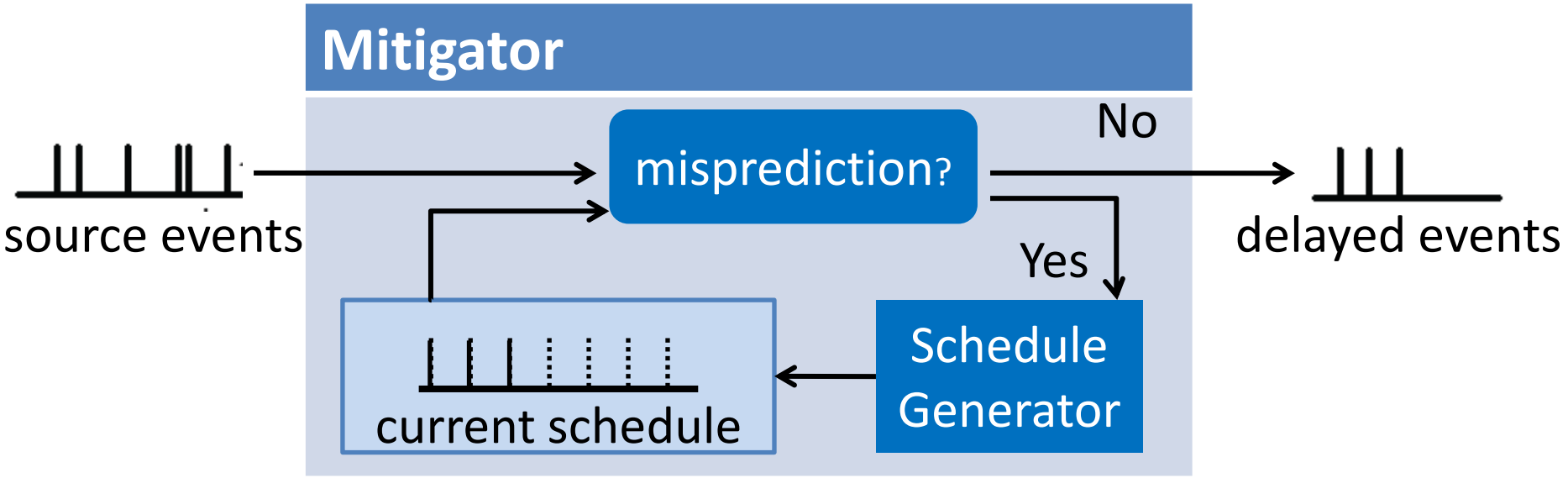
Insight: Use Public Information

- Previous black-box model
  - No misprediction: events delivered according to schedule
  - Misprediction: entire schedule is **statically** determined (difficult for interactive systems)

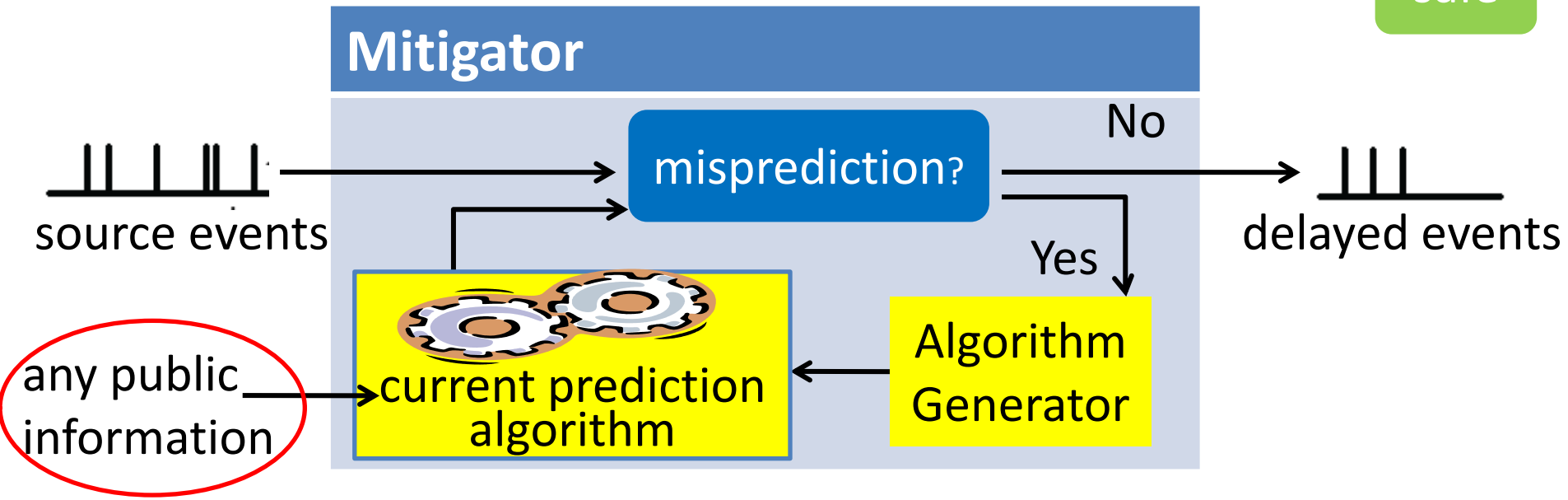
safe



Insight: Use Public Information

- Previous black-box model
  - Schedule is **dynamically** calculated by prediction algorithm
  - No misprediction: schedule is deterministic given public info.
  - Misprediction: select a new prediction algorithm

safe



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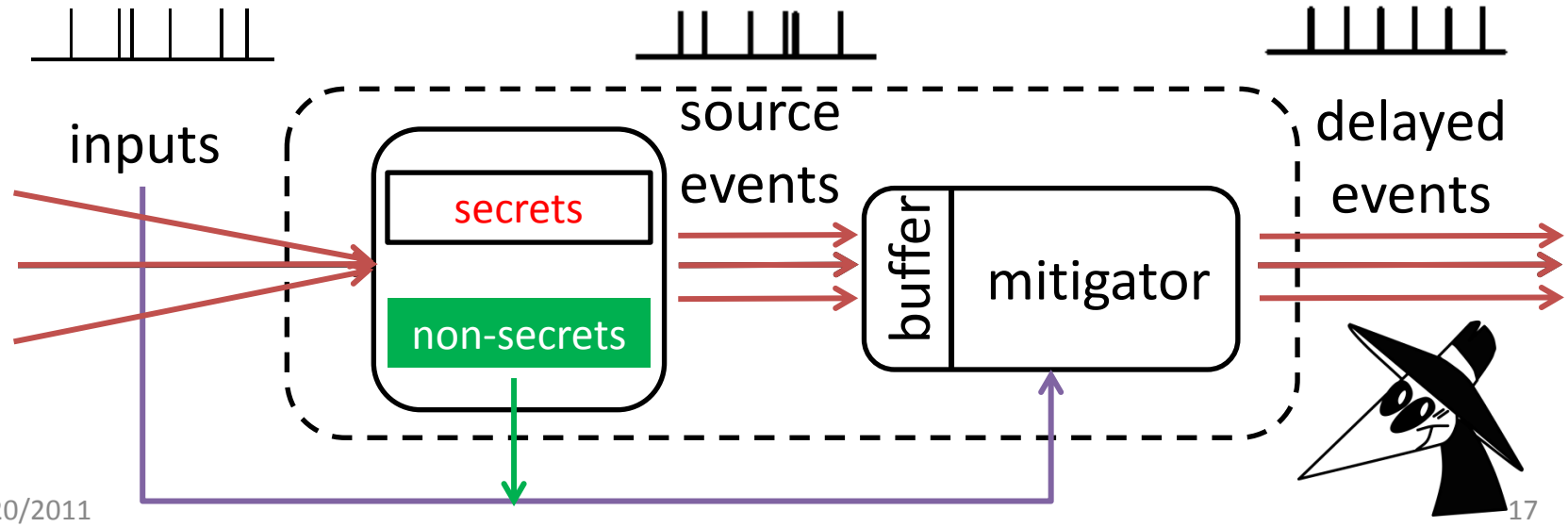
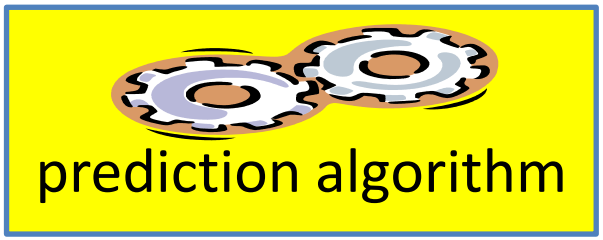
Public Information

- Public information in interactive systems
  - ***Request types:*** public payloads in requests, such as URLs
    - www.example.com/index.html vs. www.example.com/background.gif
  - ***Public information in system***: such as input times
  - ***Concurrency model***



Prediction with Public Information



Epoch #

- Prediction for request type *r*: *p (N, r)*
- Schedule (output time) for i^{th} event in the N^{th} epoch
  - Single thread

Start time

Handling time

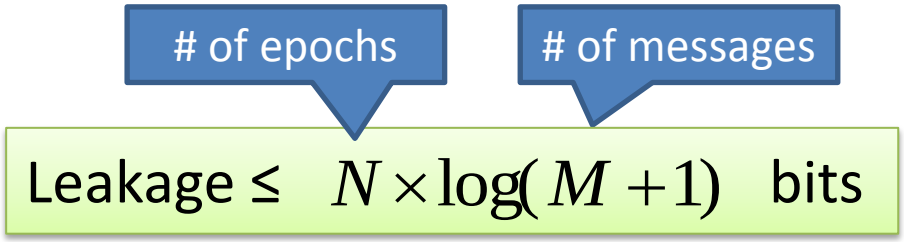
$$S_N(i) = \max(inp_i, S_N(i-1)) + p(N, r_i)$$

  - Multiple, concurrent threads
    - Calculated in similar ways

Schedules are computed dynamically within each epoch using only *public* information

Information Leakage

- Information still leaks via ***mispredictions***!
- Formal result



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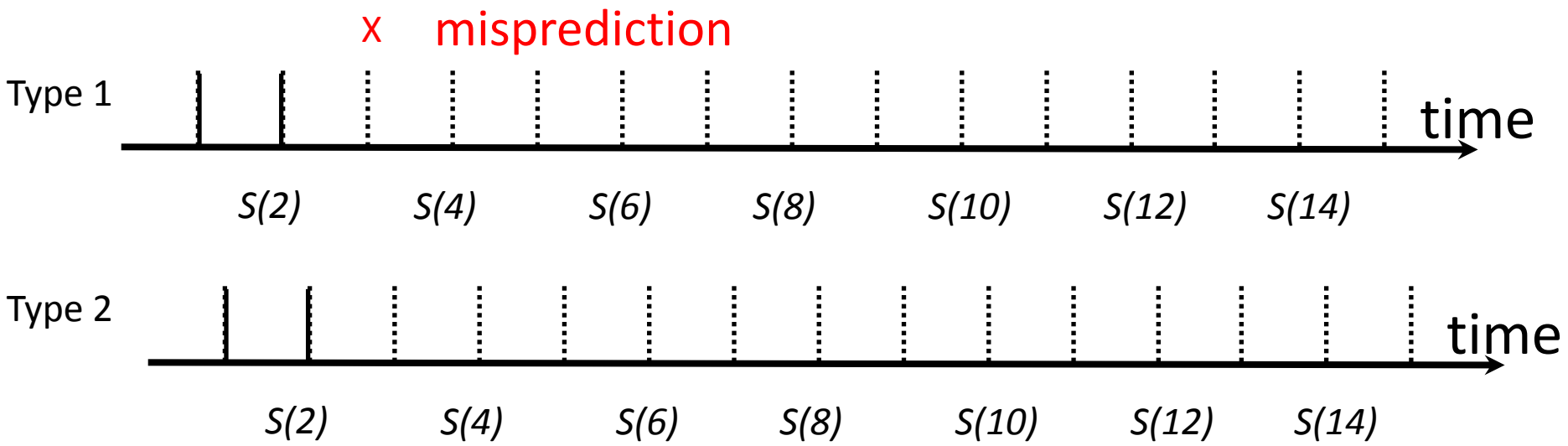
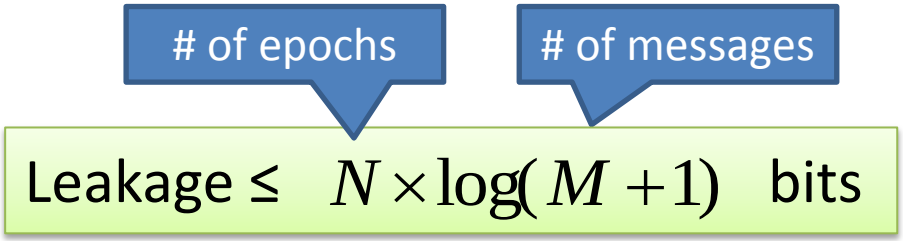
Penalty Policy – What



Penalty policy

- ***Which*** type should be penalized?
- ***How much*** it should be penalized?

Penalty Policy – Why



- Concurrency & request types also bring ***new threats***
- Request types are penalized separately (local penalty policy)
  - Attacker controls the timing of *R* request types
    - ***N* is proportional to *R***
- Penalize all request types (global penalty policy)
  - Performance is bad

Grace Period Penalty Policy

- Better trade off?
  - Information leaks via ***mispredictions***!
  - "Well-behaved" types
    - Few mispredictions, leak little information
    - Share little penalty from other types
- ***l***-level grace period policy
  - type *i* is penalized by other types only when it triggers more than ***l*** mispredictions

Leakage Analysis

- Difficult for general penalty policies
  - Influences between request types
  - Different predictions
  - Need to consider ***all*** possible input sequences
- Principled way of bounding total leakage
  - Transform into optimization problem with R constraints (formal proof & details provided in paper)

request types

Leakage Analysis

Leakage

- Global: $O(\log T \times \log M)$ (running time, # of messages)
- Local: $O(R \times \log T \times \log M)$ (# request types)
- Grace period: $O(\log T \times \log M)$
  - ***Better trade-off***

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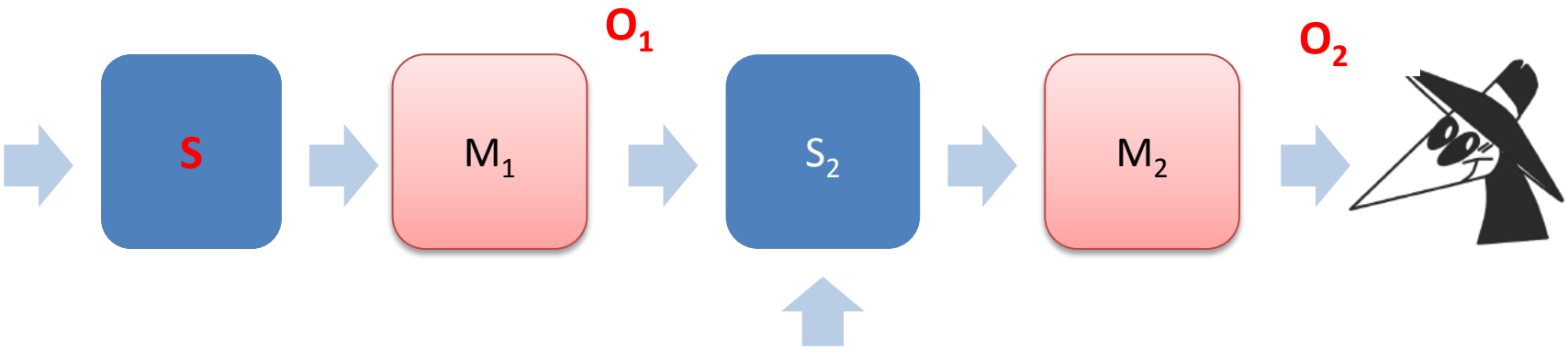
Composition of Mitigators

- Security guarantee on an interactive system that is
  - composed of mitigated subsystems

- Decompose complicated systems into 2 gadgets
  - Sequential
  - Parallel

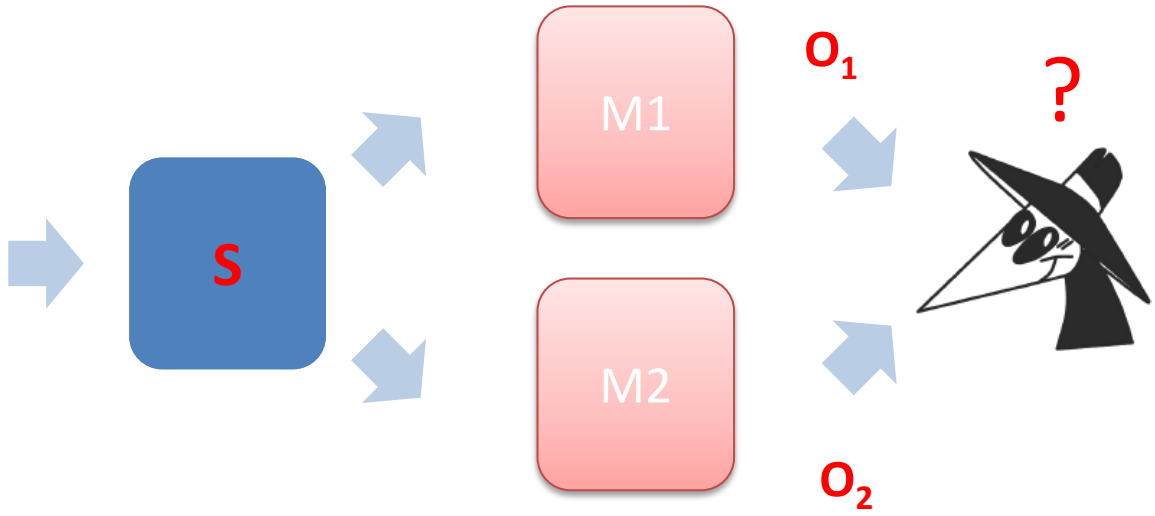
Sequential Case



Theoretical results

- Leakage in O_2 ≤ Leakage in O_1
- Valid for
  - mutual information
  - min-entropy

Parallel Case



Theoretical result

– Leakage in O_1 and O_2 ≤ Leakage in O_1 + Leakage in O_2

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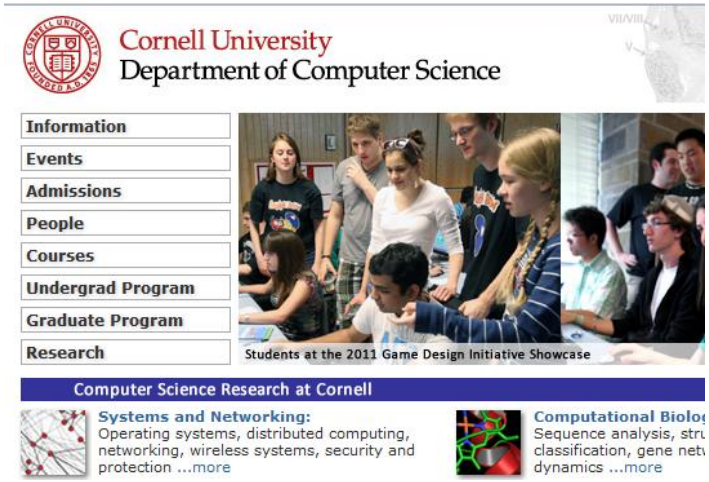
Evaluation

Real-world web applications (with HTTP(S) proxy)

Real-world applications

Proxy

Client



Mitigating Proxy

Demo

Evaluation

Measurements

- **Performance**: round-trip latency from the client side
- **Security**: leakage bounds in bits

Experiments with Web Applications

Parameters

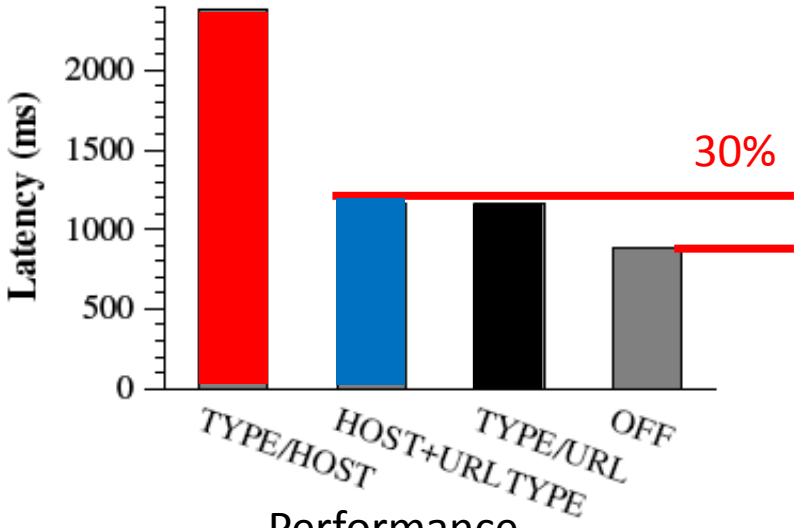
- 5-level grace period policy
- Doubling scheme
- Various request types
  - TYPE/HOST
  - HOST+URLTYPE
  - TYPE/URL

Experiments with Web Applications

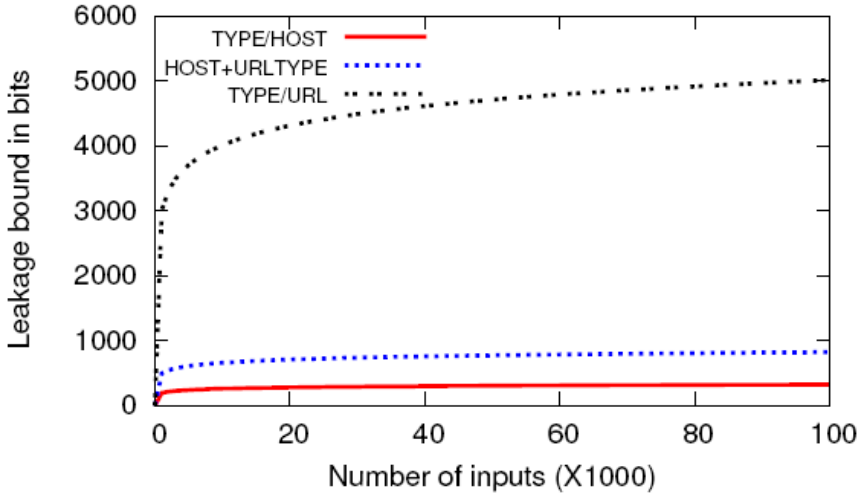
Mitigating department homepage via HTTP

(**49** different requests)

- Predictive mitigation gains good balance (**HOST+URLTYPE**)
  - About **30%** latency overhead
  - At most **850bits** for 100,000 inputs



Performance

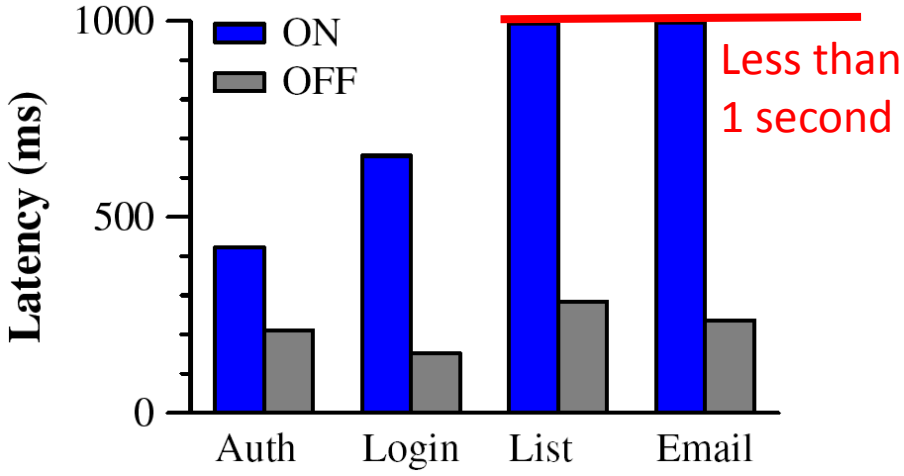


Security

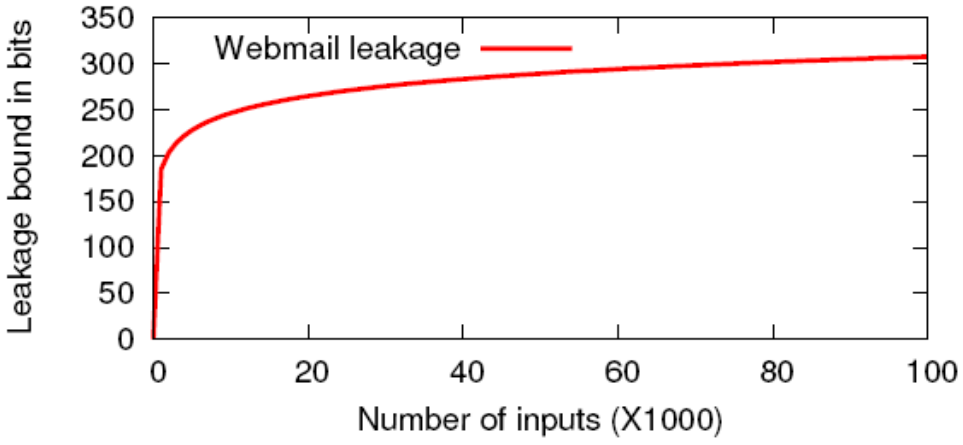
Experiments with Web Applications

Mitigating department webmail server via HTTPS

- Secure-sensitive (URL is encrypted)
- At most 300 bits for 100,000 inputs
- At most 450 bits for 32M inputs (1 input/sec for one year)



Performance

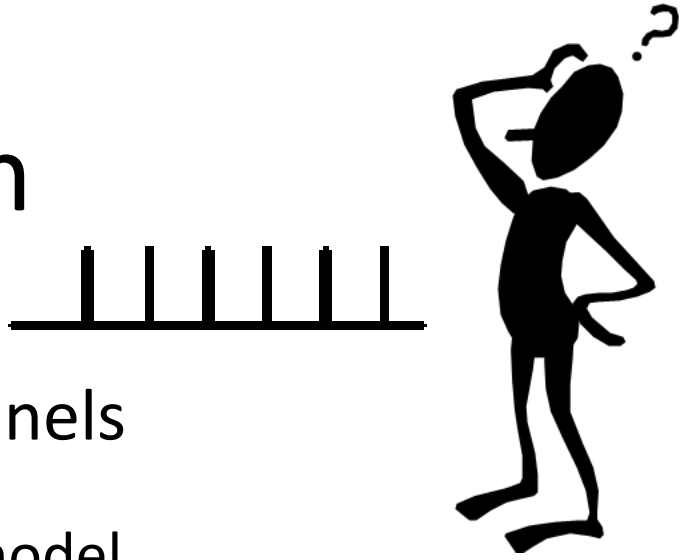


Security

Related Work

- Timing mitigation for cryptographic operations [Kocher 96, Kopf & Durmuth 09, Kopf & Smith 10]
  - Assumes input blinding
- NRL Pump/Network Pump [Kang et. al. 93, 96]
  - Only address covert channels from input acks
  - Linear bound
- Information theory community [Hu 91, Giles&Hajek 02]
  - Timing mitigation based on random delays
  - Linear bound

Conclusion



Predictive mitigation of timing channels

- Generalized predictive mitigation model

  More public information→ better performance

- General penalty policies & leakage analysis

- Composition of mitigated systems

- Evaluation suggests this technique is practical