Timing Attacks Have Never Been So Practical:

Advanced Cross-Site Search Attacks

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About me: Nethanel Gelernter

- Security Researcher / Hacker
  - Web application security
  - Ph.D., hacks, research papers, talks, etc.
- Cyberpion
  - Exploring new attack vectors & developing defenses against them
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CYBERPION

The College of Management Academic Studies

Agenda – practical timing attacks

- Cross-site search (XS-search) attacks & Response inflation
- Challenges
  - When response inflation is impossible
- Browser-based XS-search attacks
- Second-order XS-search attacks

Cross-Site Search Attacks

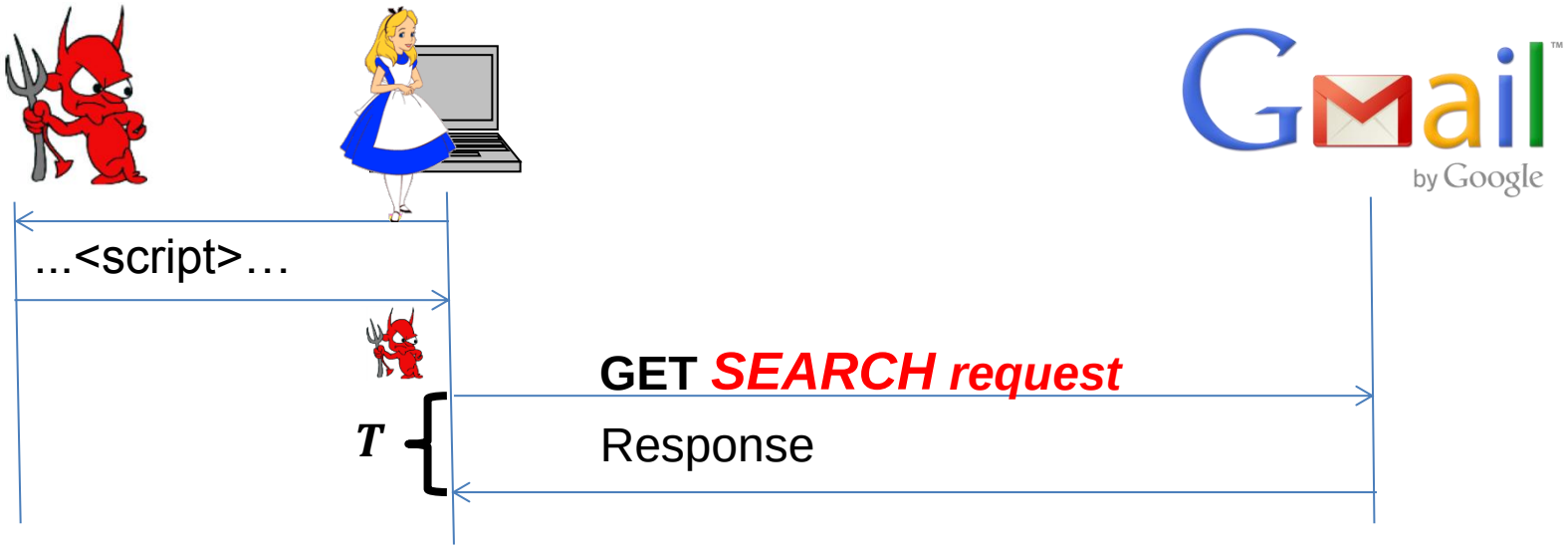
- Gelernter & Herzberg, CCS' 2015
- Exploit 'search' timing side-channel
- 'Search' in private-data kept by web-service
- **Practical:**
  - Tested on hundreds of Gmail users
    - Real world conditions
- Example: find **user name**
  - From lists of 2000 common (first and last) names
  - Takes about a minute

Cross-site attacker model

- Main model for web attacks
- The victim's browser is authenticated to services that hold private records (e.g., Gmail)
- The victim visits the attacker's website

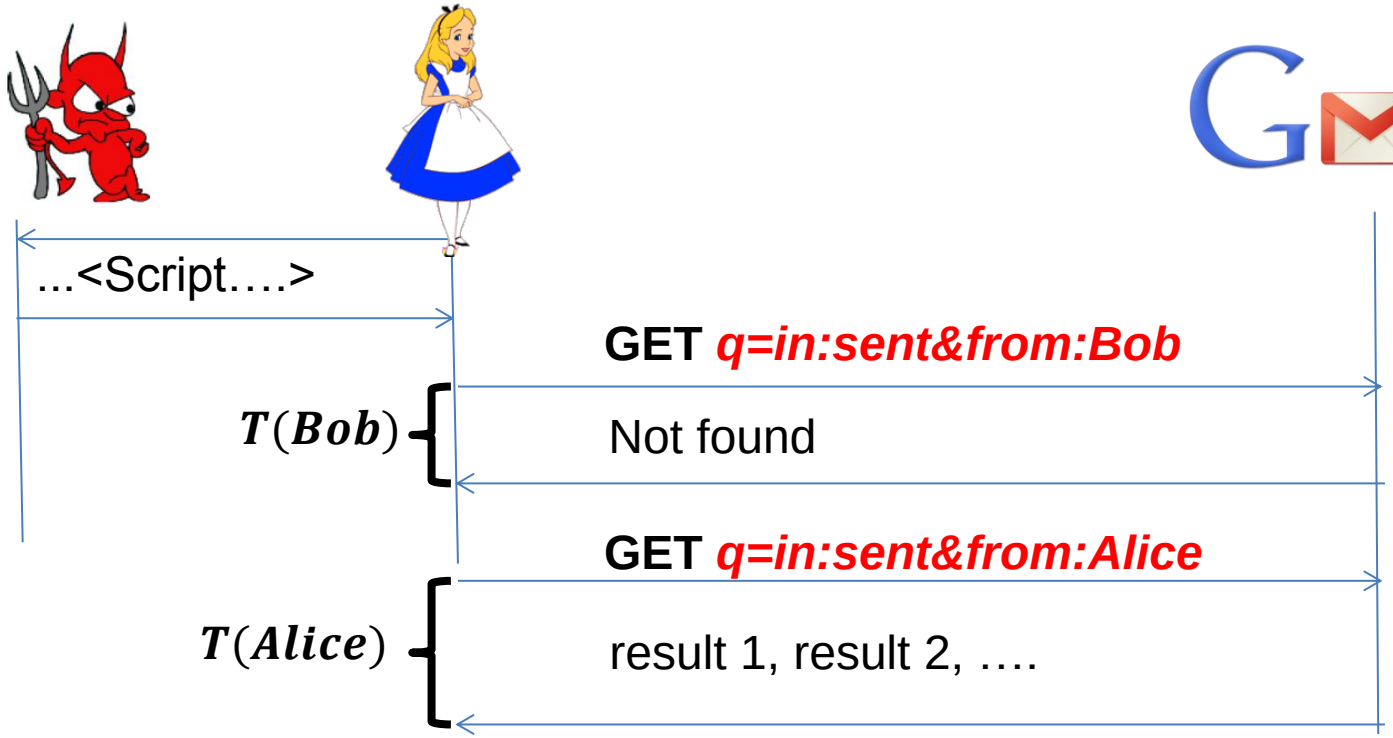
Cross-site attacker model

- Cross-site search over user's data in service
  - Attacker cannot access the content of the response
    - Same Origin Policy
  - The attacker can measure the response *time* (*T*)



XS-Search example: user name

- Find out whether the user is Alice or Bob…
- Compare:
  - *T(Bob):* response time for ‘messages sent by Bob’
  - *T(Alice):* response time for ‘messages sent by Alice’



What else can XS-Search expose?

Structured information

Contacts

Name

Email content

Outlook

Gmail by Google

YAHOO!

twitter

Relationships (follows, …)

bing

Search History

XS-Search: Basic Flow

- Find the answer for a Boolean question

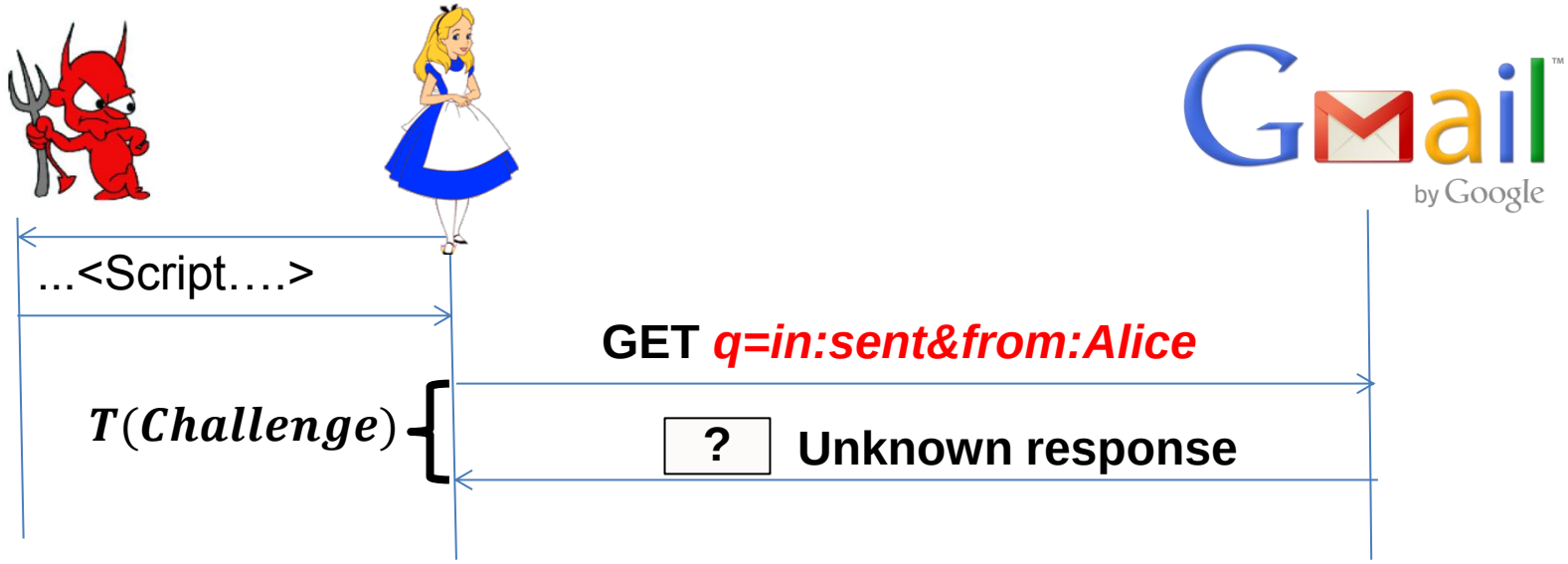
- Three steps:
  - Transform the question into a search request
  - Send search requests and collect samples
  - Analyze response times ➔ answer the question!

XS-Search: Basic Flow – 1st Step

- Is the name of the user *Alice*?
  - in:sent from:Alice
- Is she related to bob@gmail.com?
  - bob@gmail.com&st=100
- Does Alice have an affair with Charlie
  - “I love you” to:Charlie from:Alice

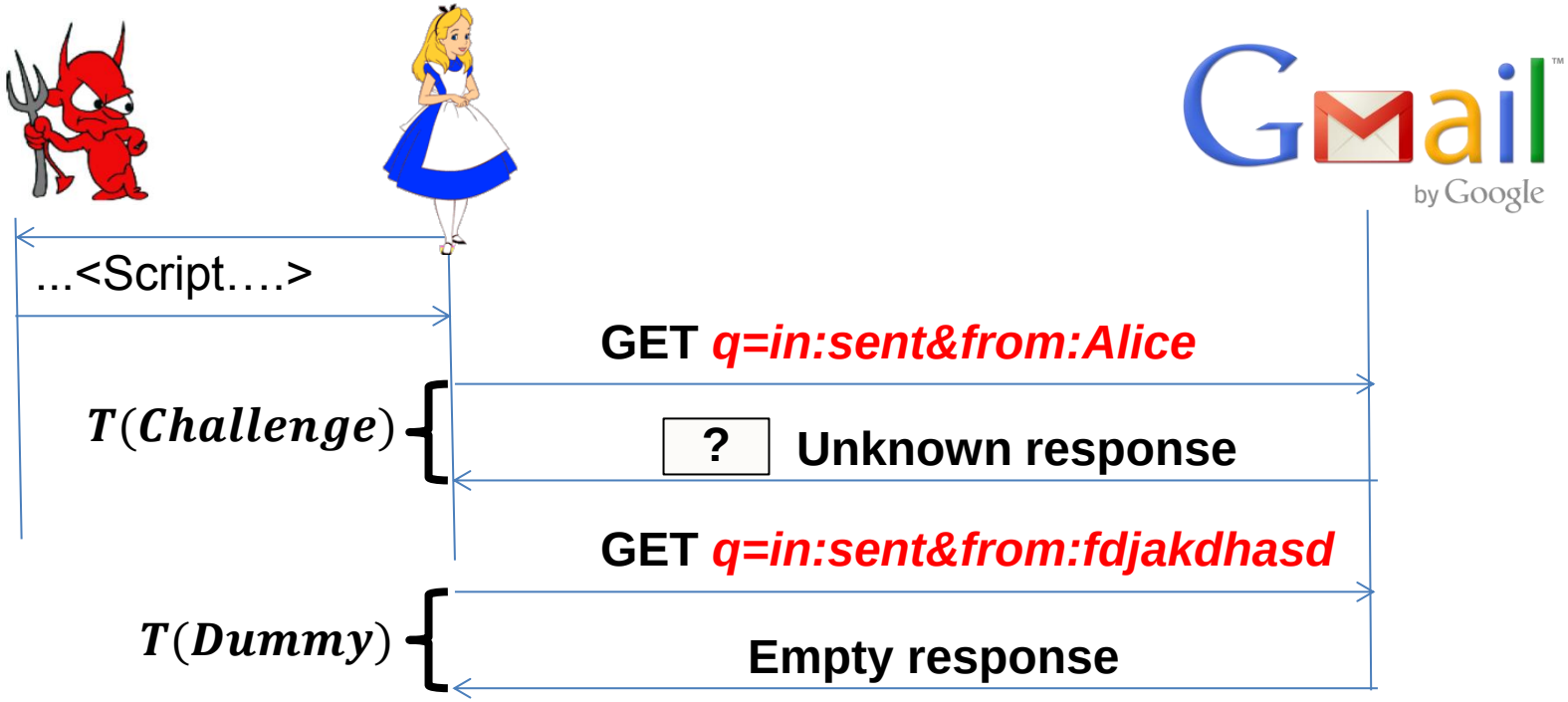
XS-Search: Basic Flow – 2nd Step

- Send a **Challenge** request
  - Is the user name *Alice*?
    - True: a **Full** response is returned (has some content)
    - False: an **empty** response is returned

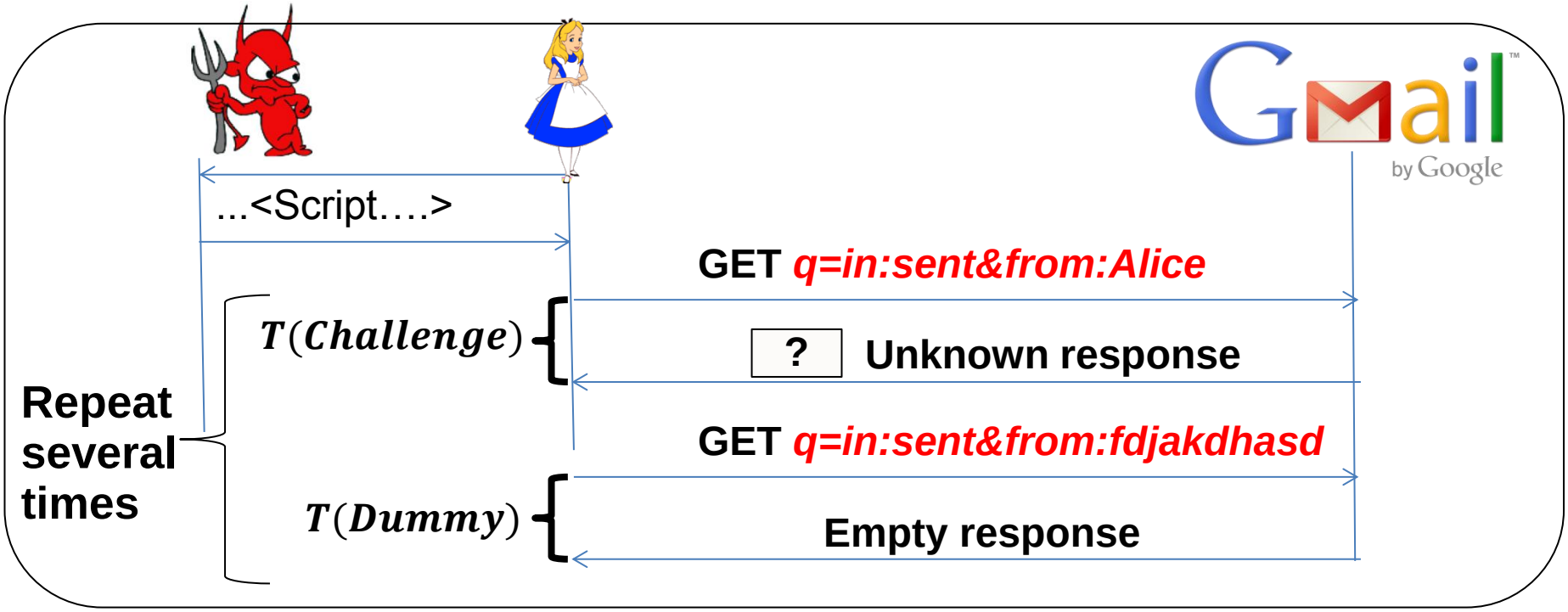


XS-Search: Basic Flow – 2nd Step

- Send a **Dummy** request
  - Is the user name ***fdjakdhasd***?
    - The response is expected to be **empty**



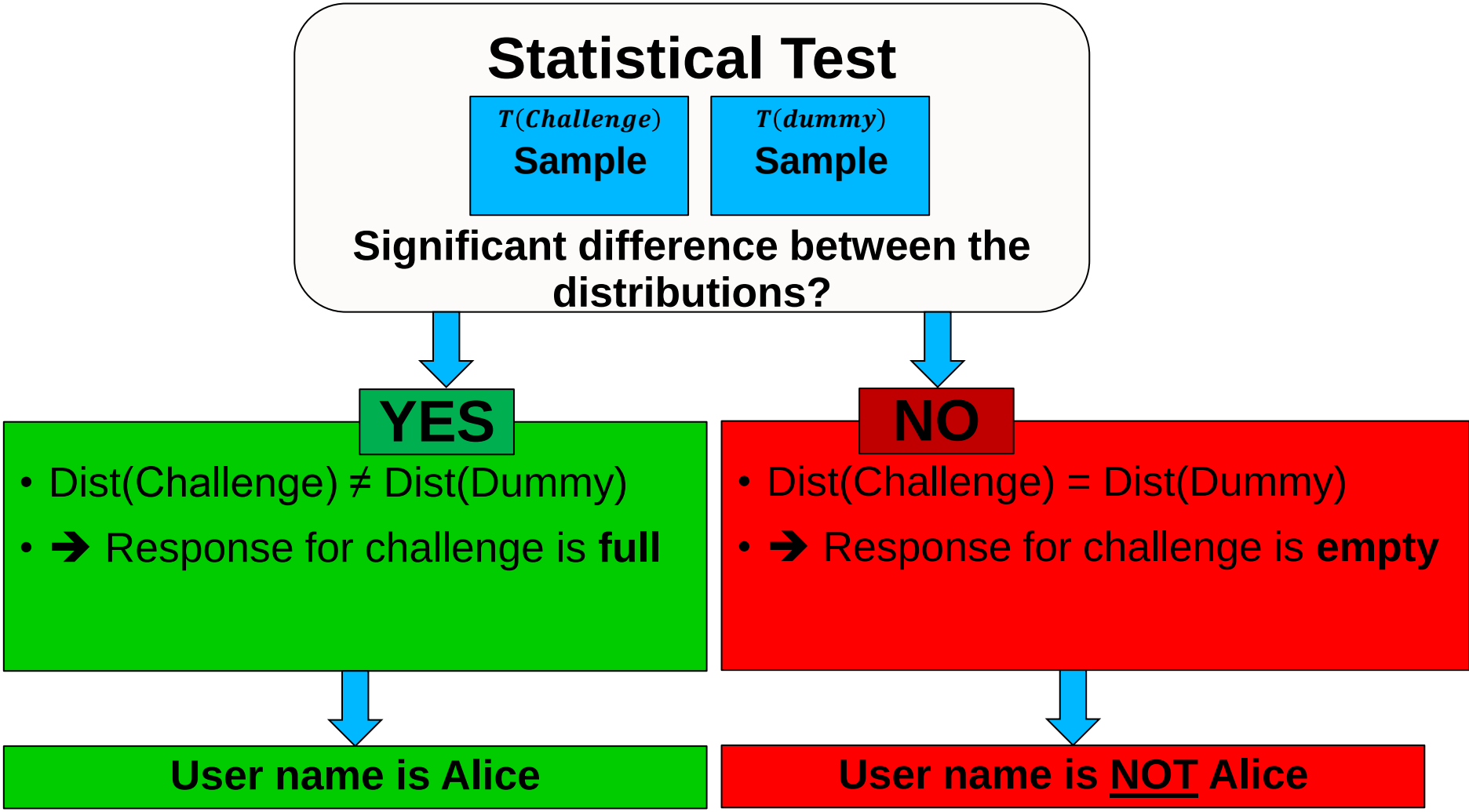
XS-Search: Basic Flow – 2nd Step



T(Challenge) **Sample**

T(dummy) **Sample**

XS-Search: Basic Flow – 3rd Step



Practical timing attacks: challenges

- Timing attacks
  - Delays depend on dynamically-changing factors, e.g.: Congestion and concurrent processes in client and server
- Practical attacks
  - Minimal time
    - Exploit also short visits of users
  - Minimal number of requests
    - Avoid detection and blocking
      - E.g., by server's anti-DoS defenses

Response Inflation

- Increase the size difference between **full** and **empty** responses
- Larger difference in size → Larger difference in time

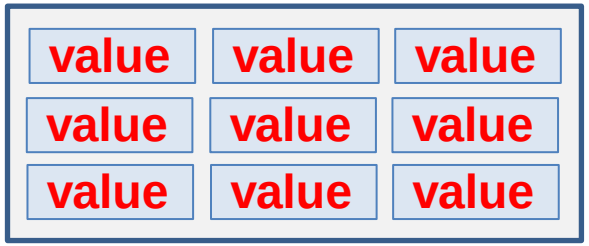
Larger → Slower

Response Inflation

- Search requests have many parameters
- Some of them are reflected in the responses **as a function of the number of results**

https://example.com/search?reflected_parameter=**value**

Empty response



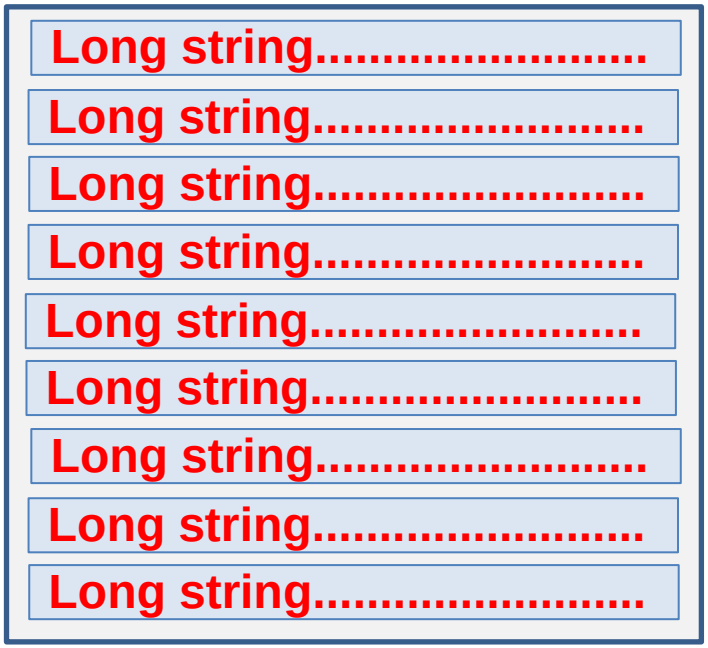
Full response

Response Inflation

- Sometimes, the attacker send **very long strings** as the value of the reflected parameter

https://example.com/search?reflected_parameter=**Long string**

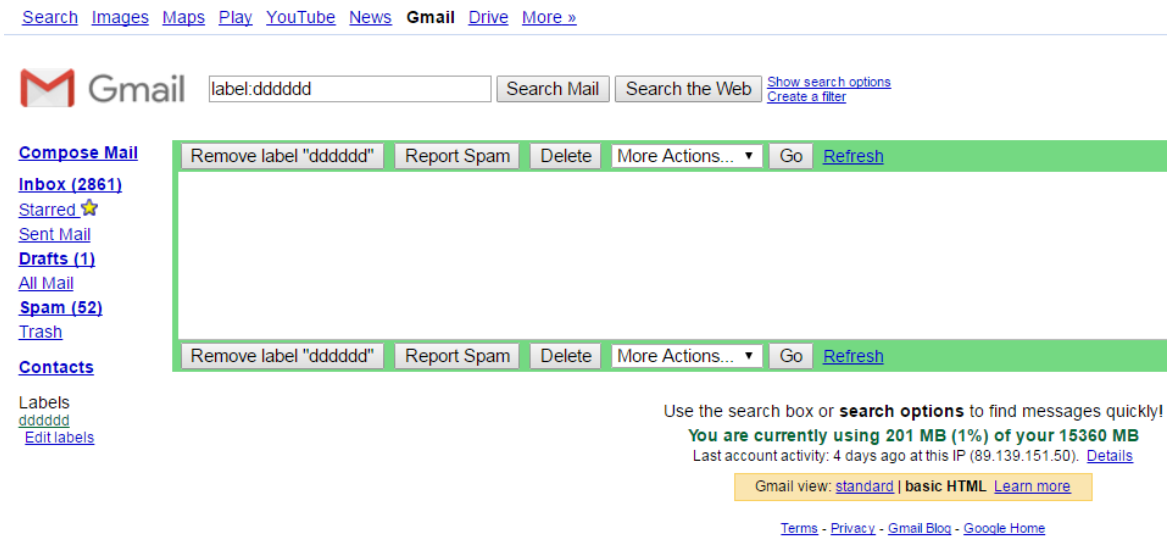
Empty response



Full response

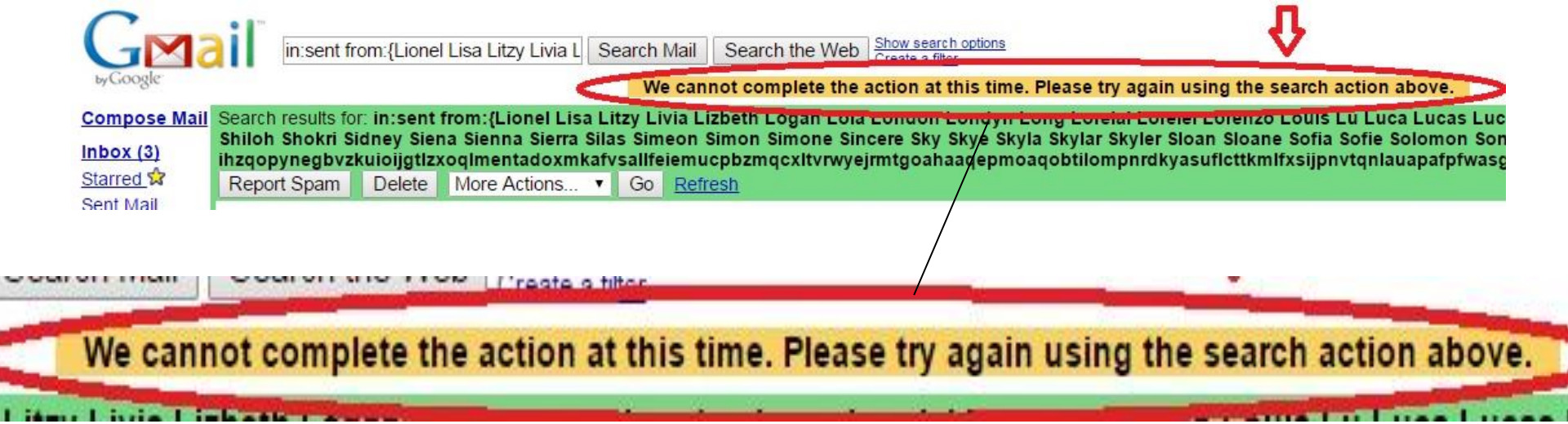
Response inflation example

- Exploiting Gmail search in the HTML view
- The query itself!
  - Appears once for each entry (50 max by default)
  - Can be inflated to 8KB
- Up to 400KB response size inflation!



But…

What if there is no response inflation?



What if there is no response inflation?

- Browser-based XS-search
  - When there is **some** difference in the response size
- Second-order XS-search
  - When there is **no** difference in the response size!

Browser-based (BB) XS-Search

- Statistical tests and divide and conquer algorithms
  - Gelernter & Herzberg, CCS' 2015
- Browser-based timing side channel
  - Van Goethem et al., CCS' 2015
- Algorithmic improvements

Classical vs. BB timing attacks

- Classical timing attacks:
  - Load the resources from the server several times to collect time measurements
- Browser-based timing attacks:
  - Load all the resources from the server once and cache them
  - Then load them from the cache many times to collect time measurements

Classical vs. BB timing attacks

- Exploiting / measurements affected by
  - Classical: network delay, server processing time, browser processing time
  - Browser-based: browser processing time
- Can be used to differentiate between
  - Classical: large/small resources, high/low server processing time
  - Browser-based: large/small resources

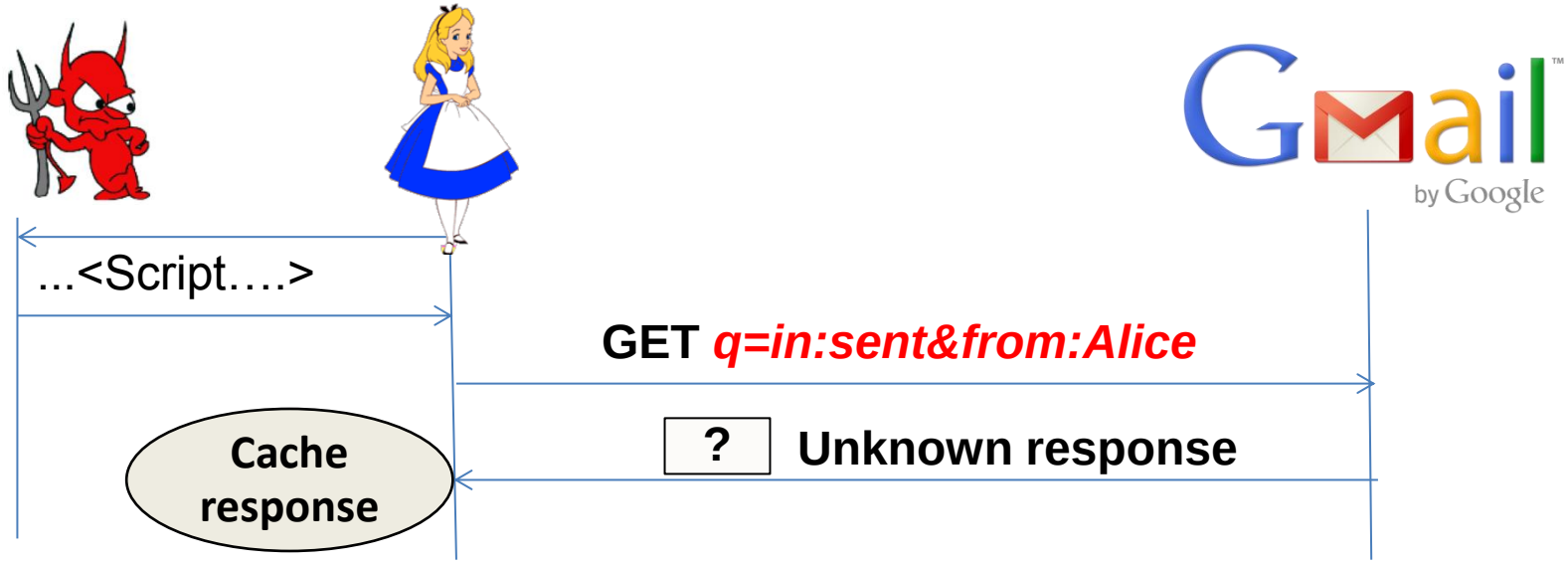
BB XS-Search: Basic Flow

- Find the answer for a Boolean question

- Changing only the second step of the original XS-Search attack

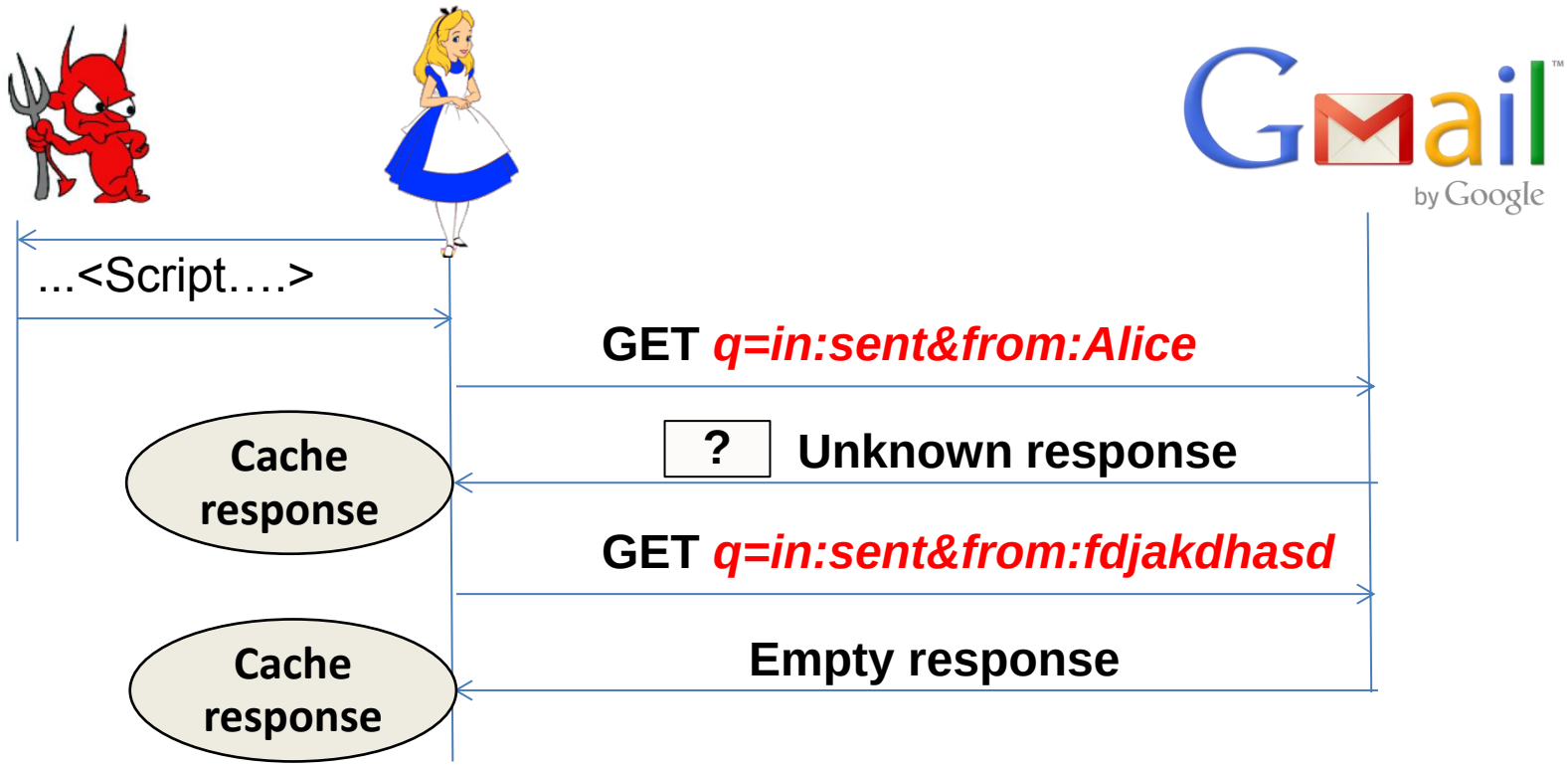
BB XS-Search: Basic Flow – 2nd Step

- Send a **Challenge** request
  - Is the user name *Alice*?
    - True: a **Full** response is returned (has some content)
    - False: an **empty** response is returned



BB XS-Search: Basic Flow – 2nd Step

- Send a **Dummy** request
  - Is the user name ***fdjakdhasd***?
    - The response is expected to be **empty**



BB XS-Search: Basic Flow – 2nd Step

Gmail by Google

...<Script….>

GET *q=in:sent&from:Alice*

? Unknown response

Unknown and empty responses are cached

GET *q=in:sent&from:fdjakdhasd*

Empty response

Repeat many times

$T(Challenge)$? Unknown response

$T(Dummy)$ Empty response

Browser-based (BB) XS-Search

- Algorithmic improvements
- Not for Boolean questions
  - Basic flow – only Boolean questions
    - Is the victim's name Alice?
- Answering multiple choice questions
  - E.g., which names out of many options are matching the victim?
- Optimally use the browser-based timing side-channel

Browser-based (BB) XS-Search

- Evaluation compared to both the previous works
- Repeating attacks/experiments done in each of them
  - Original XS-Search: extract victim's names from Gmail
  - BB timing attacks: extract victim's age from Facebook
- Significant improvement!
- In this talk: only one example

BB XS-Search vs. original XS-Search

- Gmail example
  - The goal of the attacker: extract the first and last names of the victim out of a list of 2000 names
  - XS-Search results:
    - 90% success rate (both first and last name found)
    - 1 minute on average
    - 2.6% false positive

BB XS-Search vs. original XS-Search

- How to answer multiple-answer questions efficiently?
- The optimized multiple term identification (OMTI) algorithm
  - Divide and conquer algorithm
    - Relying on the OR operator
  - **Different dummy search request is sent every round**

BB XS-Search vs. original XS-Search

- Rely on browser-based timing side-channel to optimize the OMTI algorithm

- Observation: empty responses are (almost) identical
  - No need to send dummy requests in every round
  - No need to reload the empty response in every round
    - Rely on previous measurements!

BB XS-Search vs. original XS-Search

- Evaluation of the attack on 5 different Gmail accounts
  - 15-16 times on each of them

- Significant improvement!
  - **41.6 seconds on average (compared to 1 minute)**
  - 92.3% success (compared to 89.7%)
  - 1.3% false positive (compared to 2.6%)

BB XS-Search vs. original XS-Search

- DEMO

Second-order (SO) XS-Search attacks

- The problem: sometimes the size difference is negligible

- For example: a sentence that appears in a single email

Empty response

Full response

Second-order (SO) XS-Search attacks

- Second-order attacks
  - First, manipulate the attacked web application
    - Make it (more) vulnerable
  - Exploit the vulnerability

- Second-order XS-search attacks
  - First manipulate the attacked storage
    - Create significant response inflation
  - Launch browser-based XS-search attack

Second-order (SO) XS-Search attacks

- Two SO XS-search attacks
  - Simple
  - Inflating

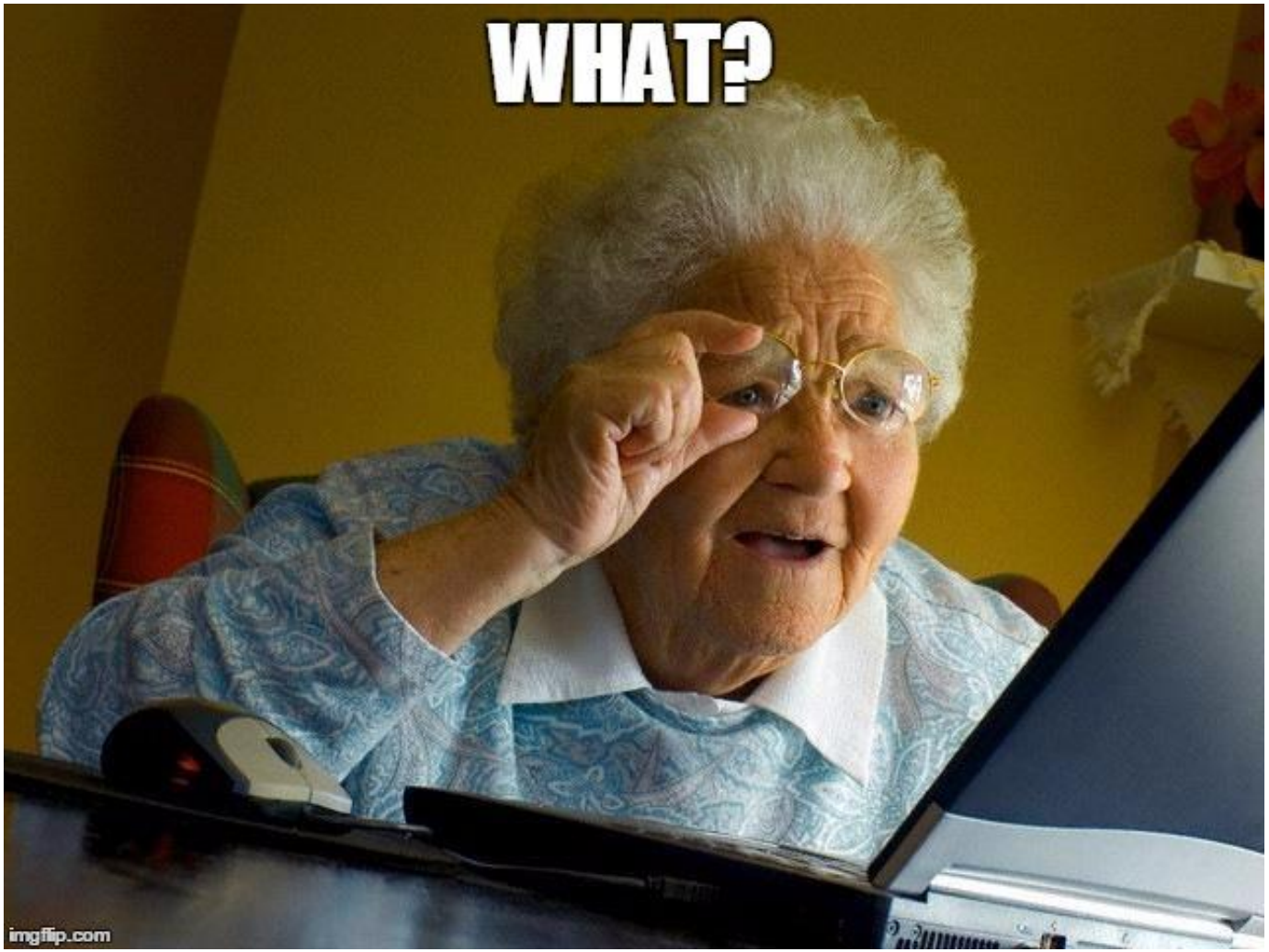
Second-order (SO) XS-Search attacks

- Model
  - Storage
  - Many records
  - A secret appears in one of the records
- Attacker can manipulate the storage remotely
  - E.g., email accounts
  - Another example later…

Simple SO XS-Search attack

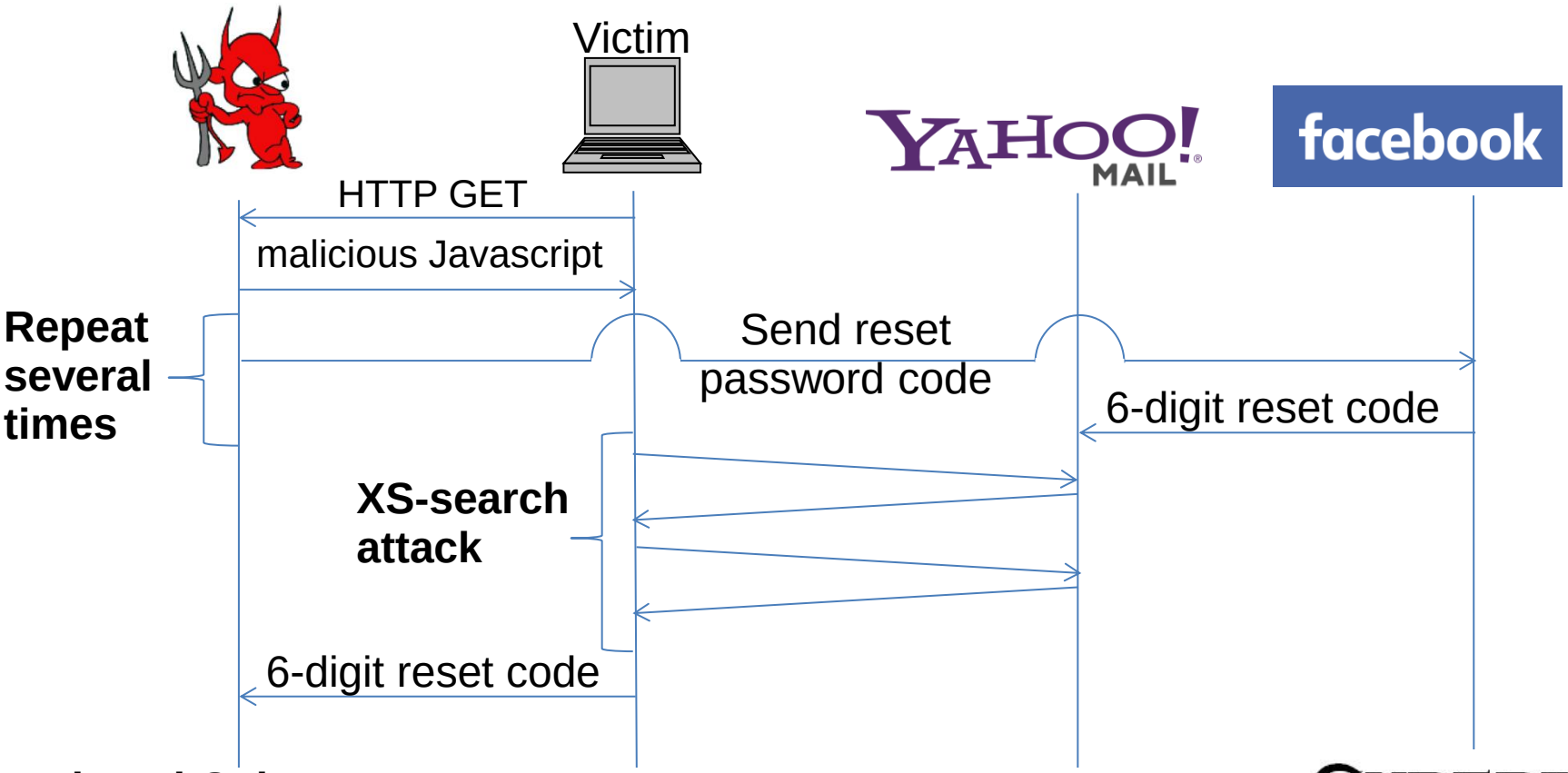
- The problem: the secret appears only once in the storage
- Simple solution: the attacker will add additional records that contain the secret!

Simple SO XS-Search attack



Simple SO XS-Search attack

- Example: extracting Facebook password-reset code from Yahoo! email



Inflating SO XS-Search attack

- Creates significant response inflation effect
  - Increase the size difference between empty and full response

- Unlike all the previous attacks: the empty response will be (significantly) larger than the full response

Inflating SO XS-Search attack

- The challenge of the attacker:
  - Find a secret out of a large dictionary of possible values
- Notations
  - ***M*** - maximal number of results
  - ***Match-all record*** – a record that contains all the possible values for the secret
  - ***Inflating record*** – a record that significantly inflates the size of every response containing it

Inflating SO XS-Search attack

- Attack process

  First part:

  – Plant one ***match-all inflating*** record in the storage

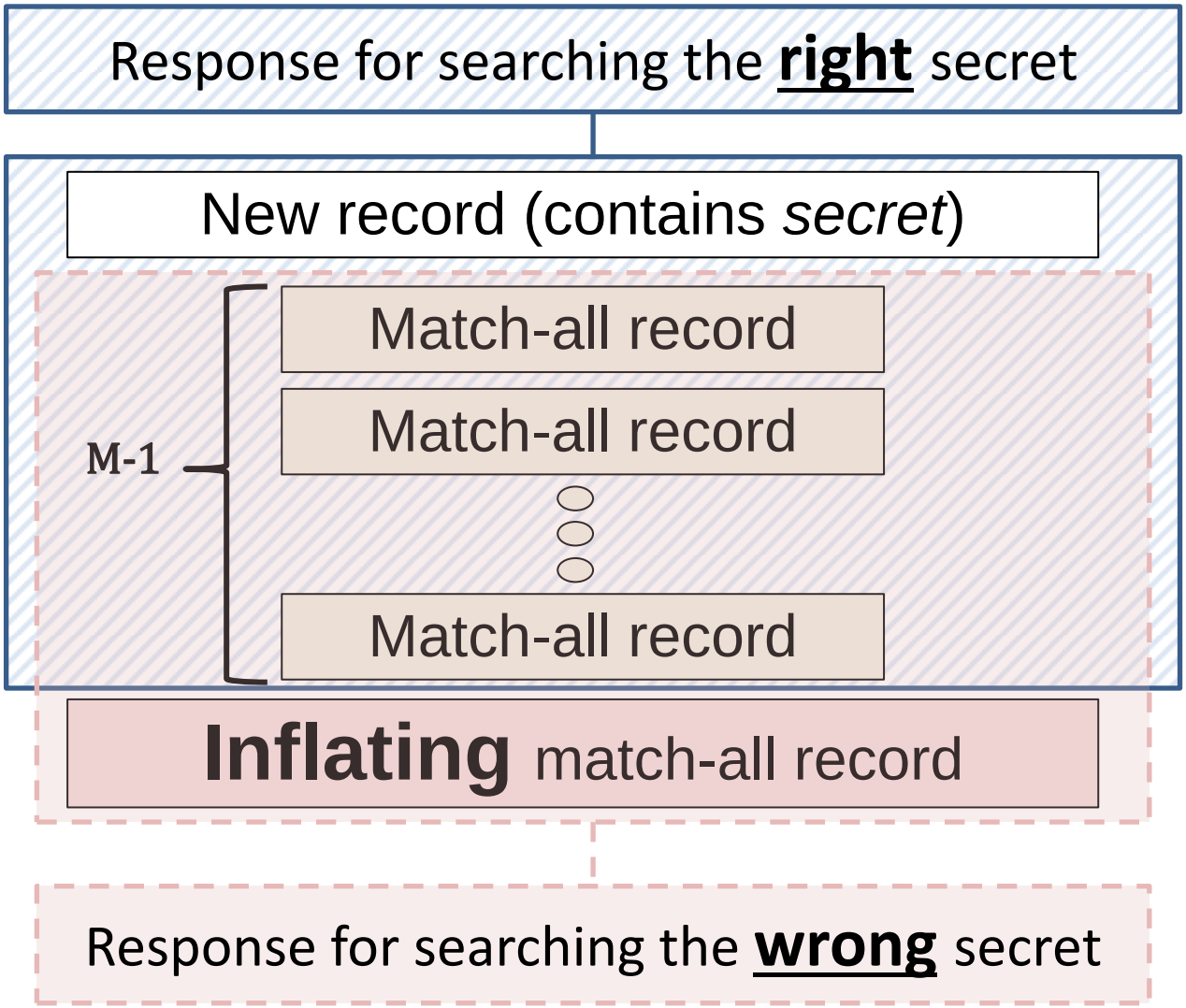
  – Plant additional ***M-1 match-all*** records

  – Additional record(s) may be added as a result of the victim's operations, or via operations triggered by the attacker

  Second part:

  – Launch BB XS-search attack!

Inflating SO XS-Search attack



Inflating SO XS-Search attack

- Inflating record in email service providers
  - Email headers
    - From
    - To

Inflating SO XS-Search attack

- Example: extracting Visa/Mastercard credit card number
  - Structured information
    - VVVV-XXXX-YYYY-ZZZZ
- First and last names: extract 2 out of 2000
  - Done successfully!
- Credit card number: extract 4 out of 10000
  - Should not be much harder

Inflating SO XS-Search attack

- Example: extracting Visa/Mastercard credit card number

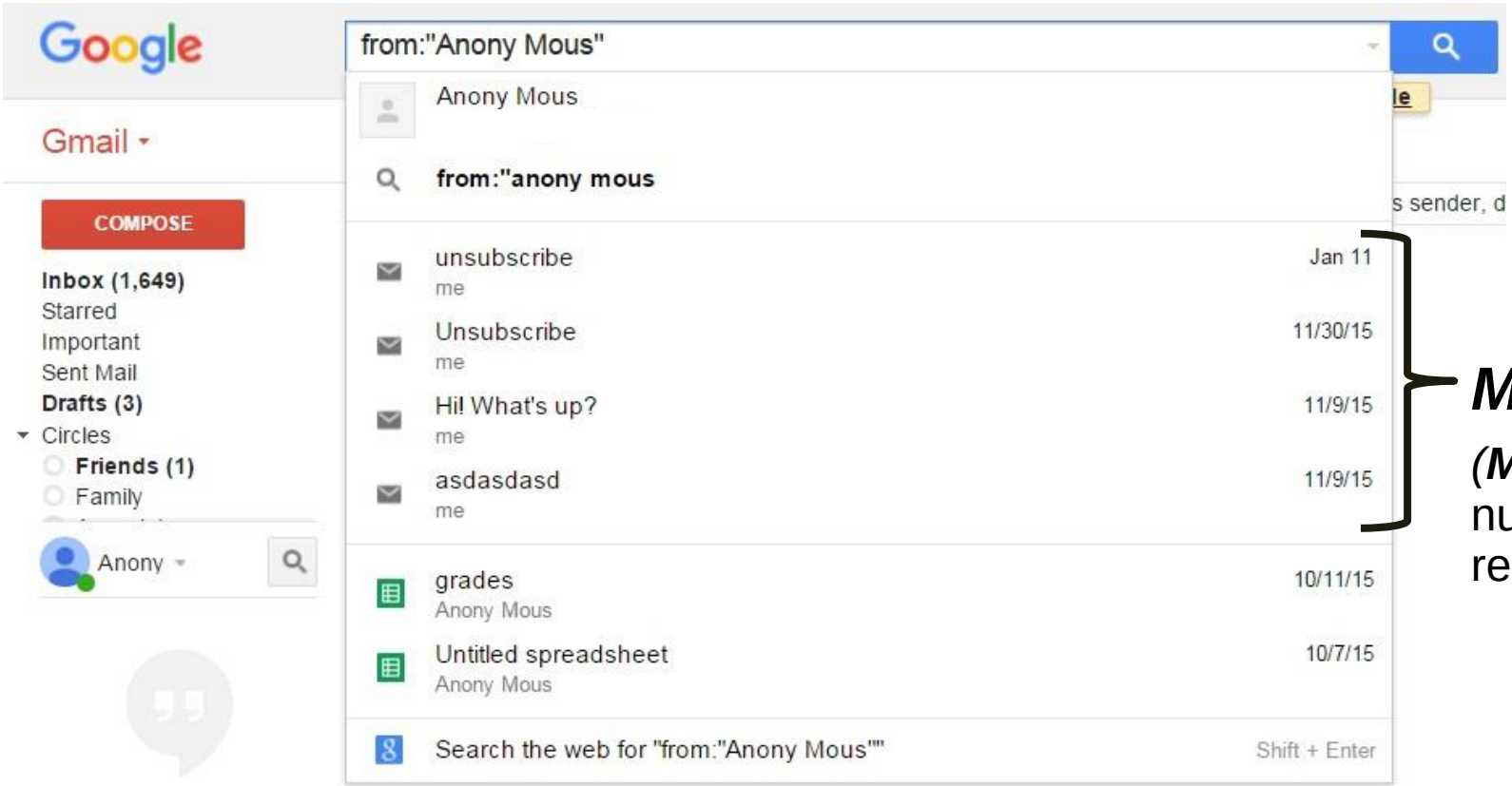
- ***Match-all record*** – a record that contains all the possible 4-digit sequences
  - Possibly as an attachment
- ***Inflating match-all record*** – a *match-all* record with very long *From* field

Inflating SO XS-Search attack

- Gmail example
- How?
  - Cross-site search requests are now blocked in both the HTML and standard views
- Cross-site search attack without sending cross-site search requests?

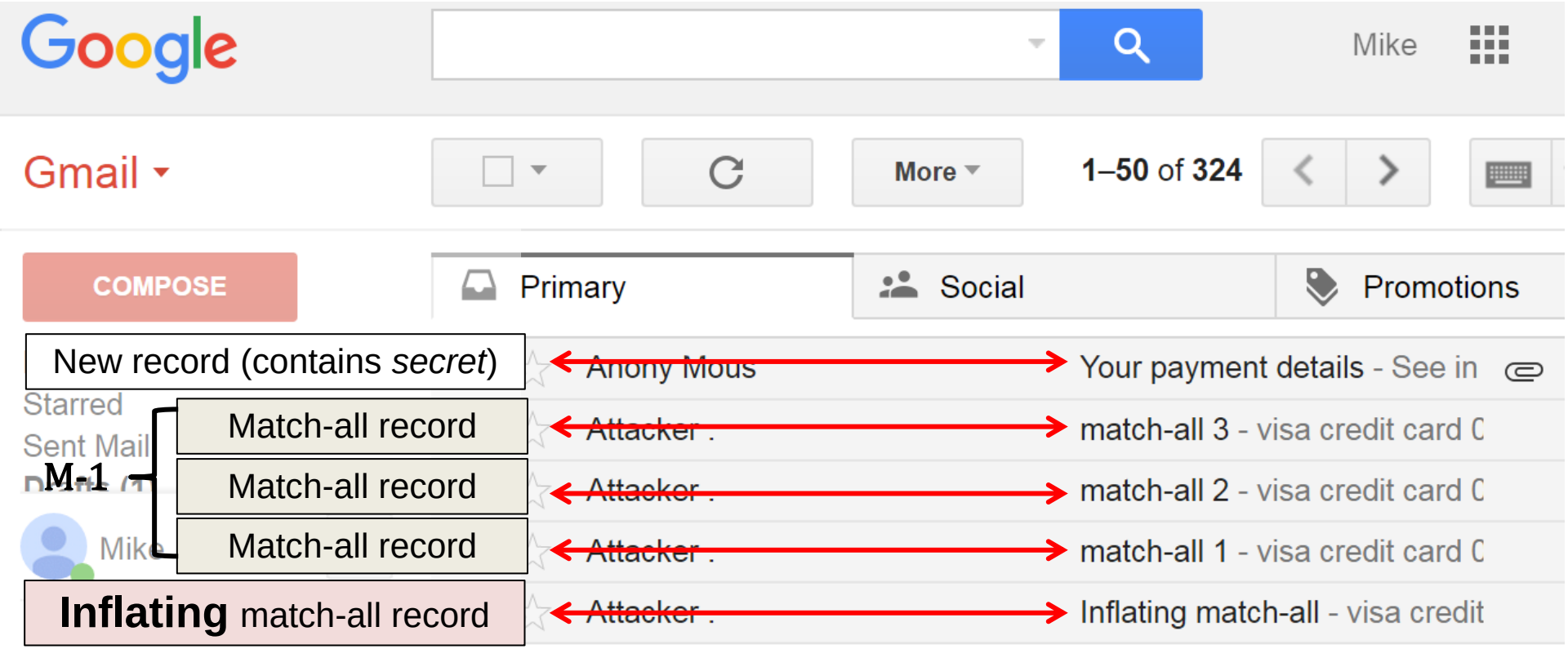
Inflating SO XS-Search attack

- Gmail example
- Exploiting the autocomplete feature!



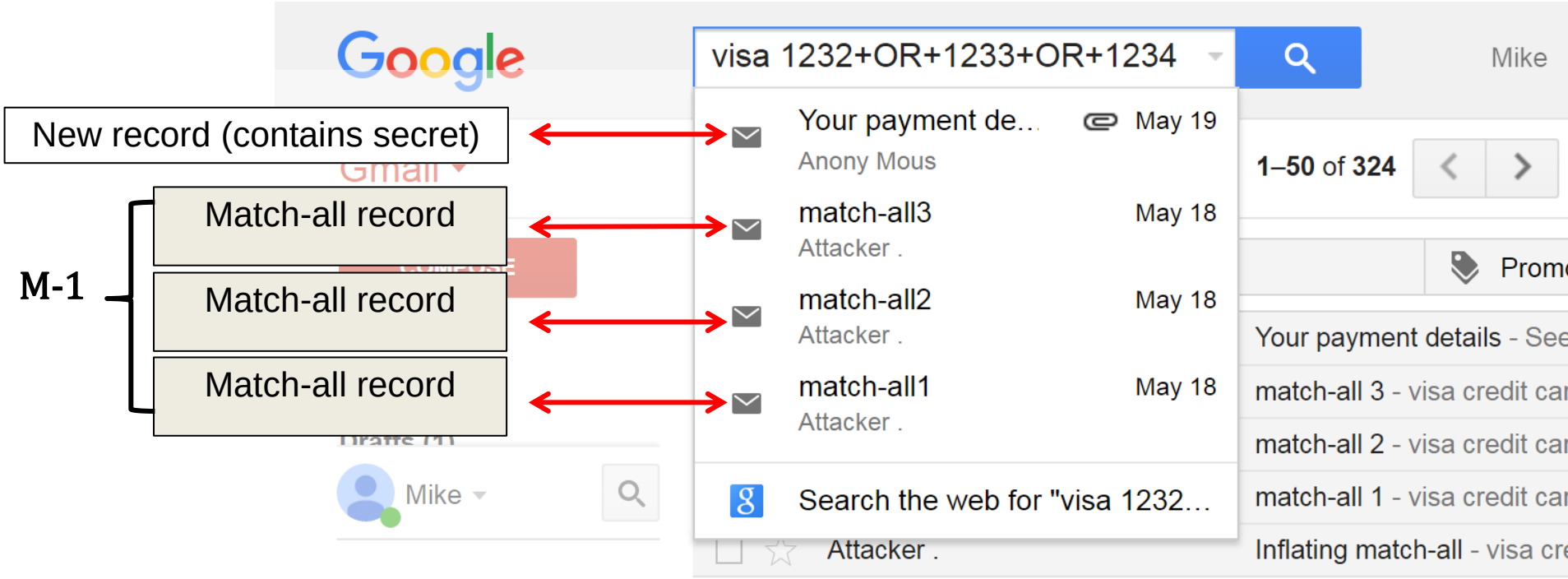
Inflating SO XS-Search attack

- Gmail example: the manipulated storage



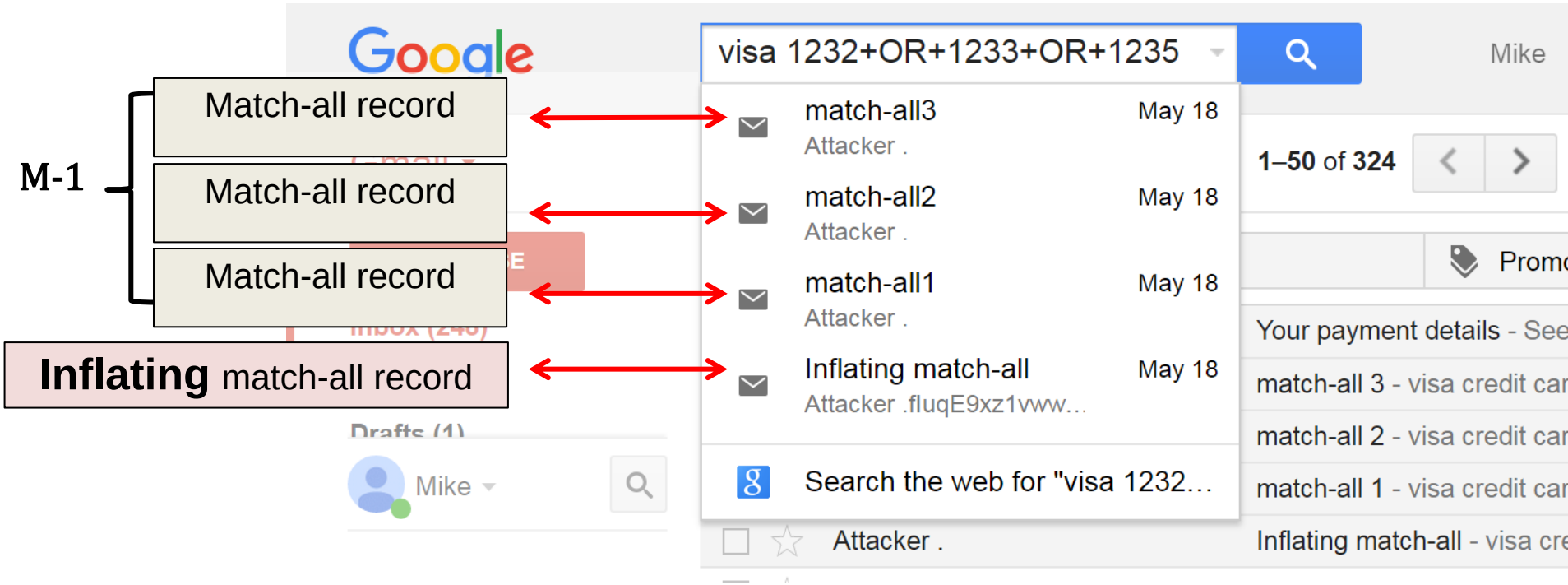
Inflating SO XS-Search attack

- Gmail example: full response (size is small)



Inflating SO XS-Search attack

- Gmail example: empty response (size is very large)



Inflating SO XS-Search attack

- DEMO

Inflating SO XS-Search attack

- Evaluation results
  - 96% success rate within less than 50 seconds
    - Yet, in the other 4% percent, 3 out of 4 sequences were found, and it was possible to detect the error and to fix it

Stealthy SO XS-Search attacks

- The challenge: manipulations on the storage can be detected!
- Solution: manipulate the storage in a way that will not be detected by the user
- HOW?

Stealthy SO XS-Search attacks

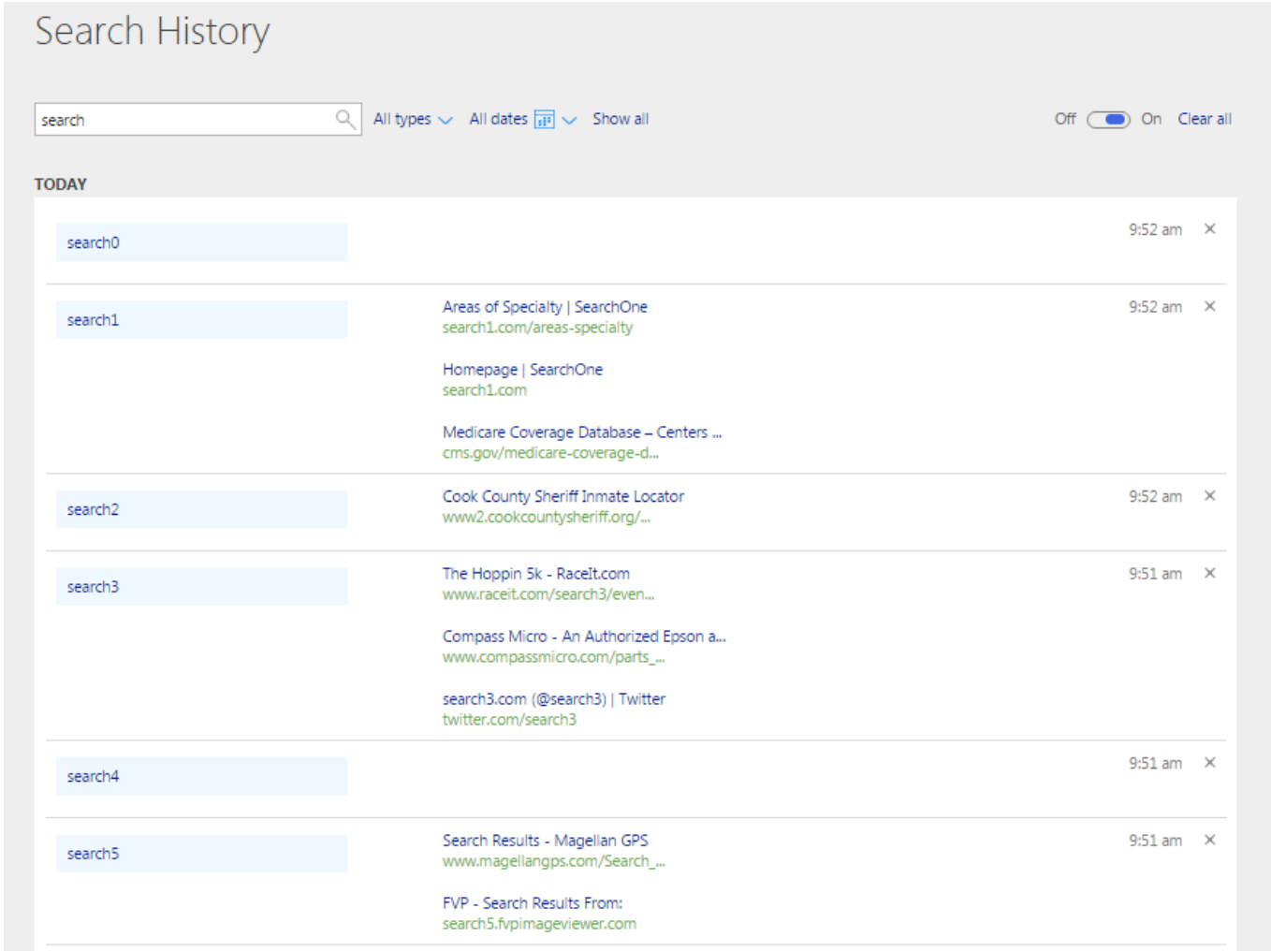
- Emails solution: abuse anti-spam mechanisms
- The planted emails will be marked as spam
  - Users do not get notifications for spam emails
  - Users (usually) do not visit their spam folder
- Only when it is possible to search in the spam and in the other folders using the same request
  - E.g., Gmail
    - in:inbox OR in:spam

Stealthy SO XS-Search attacks

- Search history
- Two requirement for inflating SO XS-Search attack:
  - Inject records to the search history log
    - **DONE**: Gelernter & Grinstein & Herzberg, ACSAC 2015
  - Inject an inflating record

Stealthy SO XS-Search attacks

- Bing example: inflating SO XS-Search attack to extract search history



Defenses (briefly)

- If possible - blocking cross-site search requests
- In other cases – make it harder to exploit
  - Block inflation techniques
  - Rate limit
- Like (almost) every other web-application attack the challenge is to find all the vulnerable spots

Conclusions

- Advanced cross-site search attacks
  - Browser-based
  - Second order
- Practical!
- Many vulnerable websites
  - Including popular ones

Thank you!

Questions?