nsdi '21

Oblique: Accelerating Page Loads Using Symbolic Execution

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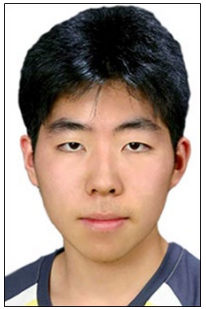


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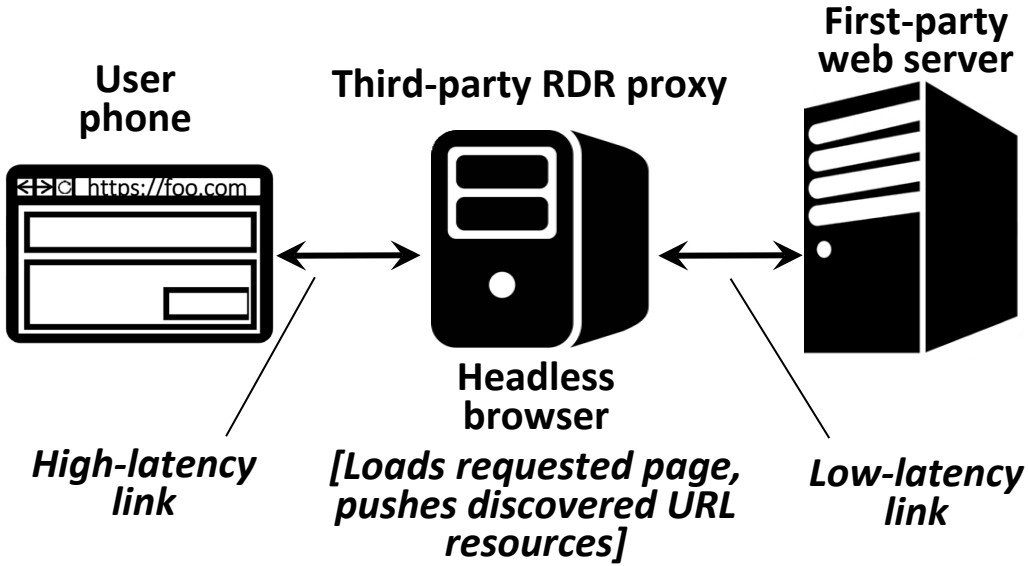
Two Problematic Trends in Web Traffic

- **Over half of web traffic is from mobile devices**
  - Many mobile users (particularly in emerging markets) stuck behind high-latency 3G/4G links
  - Even 5G links often suffer from 4G latencies
  - Latency, not bandwidth, often determines page load times!
- **Over 90% of web traffic is HTTPS, not HTTP**
  - The crypto is cheap . . .
  - . . . but how can we analyze encrypted traffic without breaking confidentiality and integrity?

Existing Web Accelerators (I)

Enables outsourcing of web acceleration

Breaks end-to-end TLS security: cleartext user data (e.g., cookies and User-Agent string) are exposed to third party

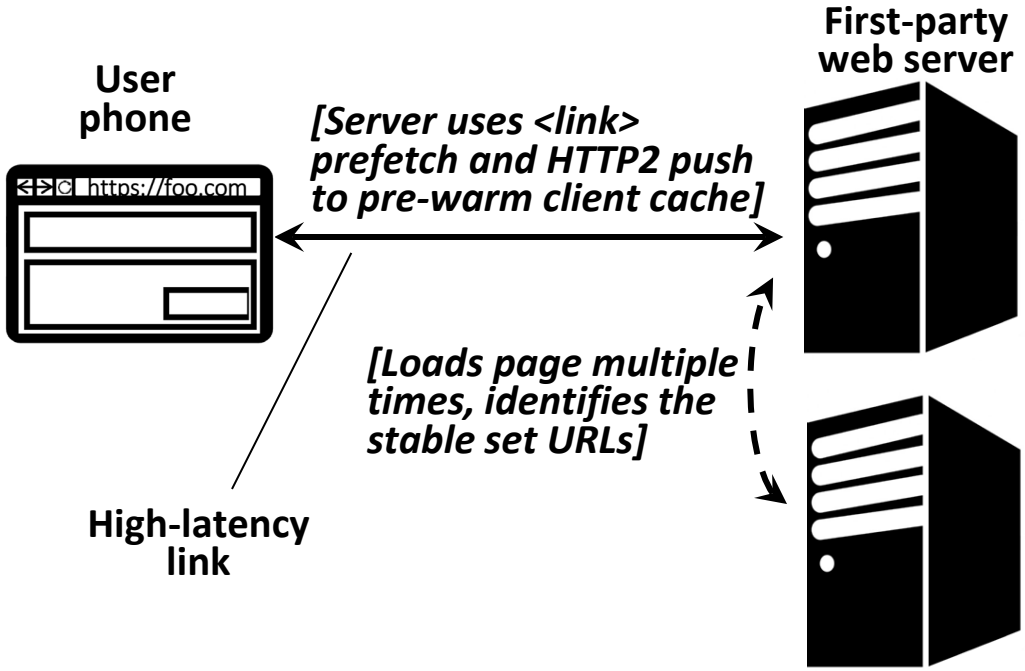


Remote Dependency Resolution (e.g., Amazon Silk, Parcel)

Existing Web Accelerators (II)

Doesn't expose cleartext HTTPS data to third parties

Analysis must be run by the first party: outsourcing it would break TLS security

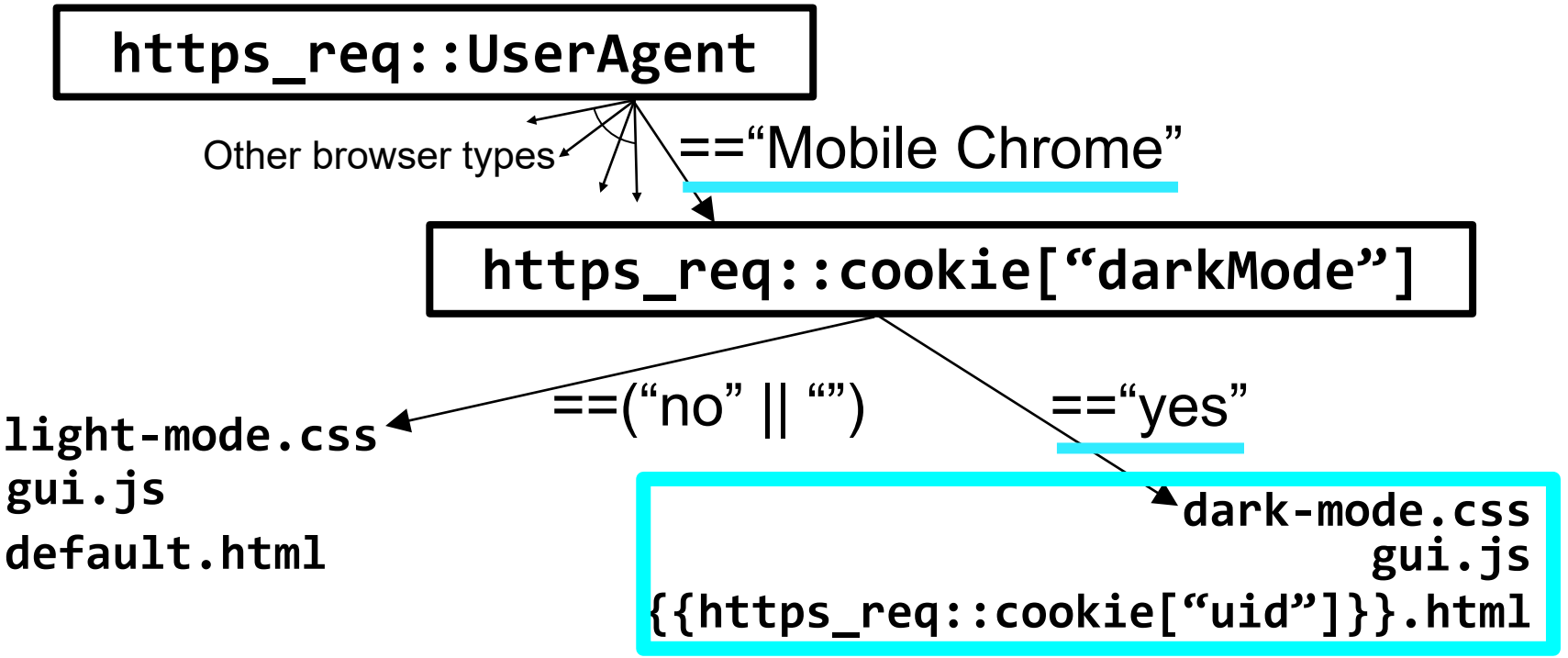


Vroom (SIGCOMM 2017)

Oblique: Acceleration + Privacy

- Have an offline third-party server load a web page **symbolically**
  - The symbols are sensitive user values like cookies and User-Agent strings
  - Output of analysis is a list of symbolic URLs fetched by the page
- Have the user's browser resolve symbolic URLs and prefetch them
- User-specific data is never revealed to the third party!

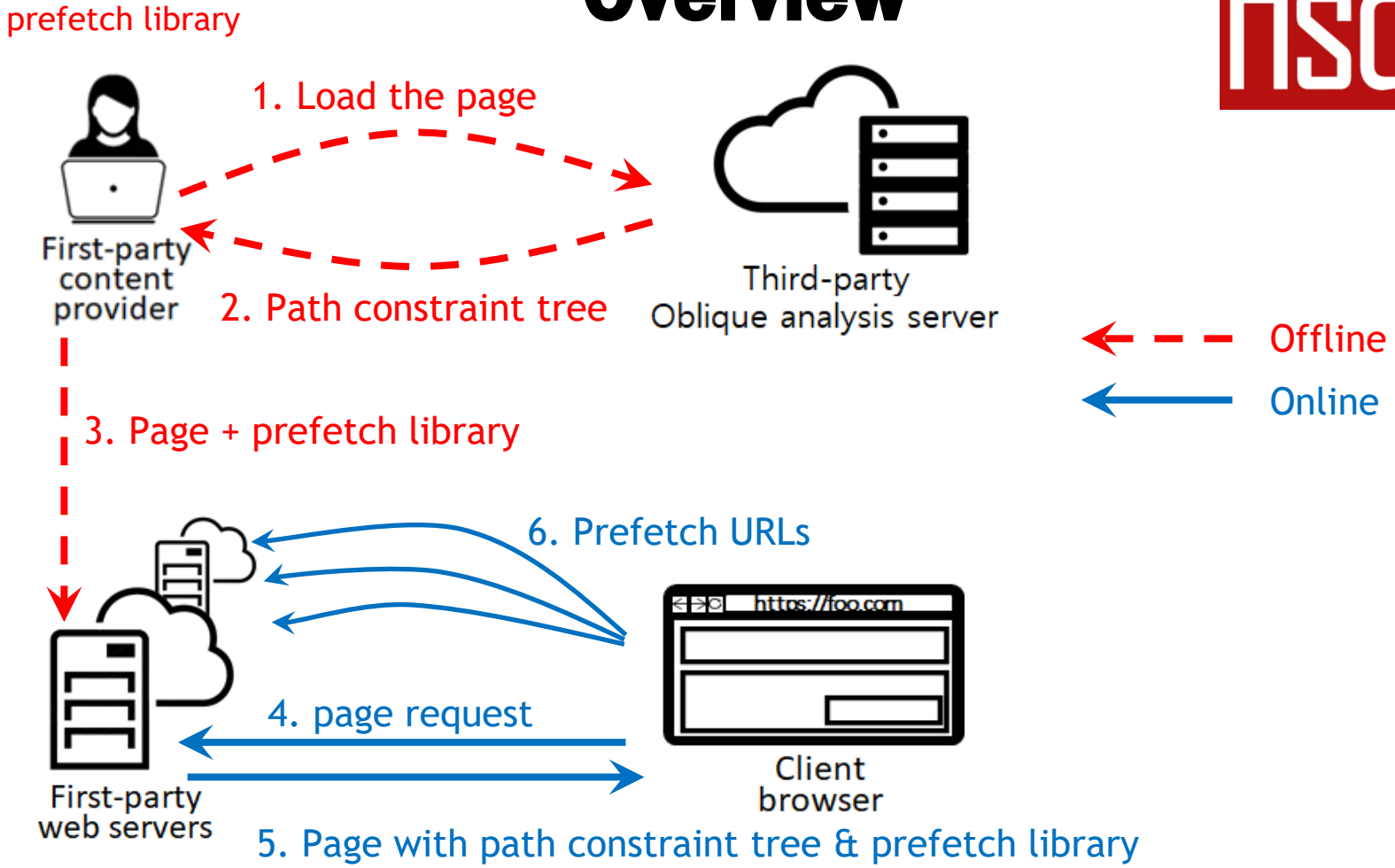
Example of a Path Constraint (PC) Tree



Client-side Symbols

Input name	HTTP header	JavaScript variable	Description
User Agent	User-Agent	navigator.userAgent	The local browser type, e.g., "Mozilla/5.0 (Windows; U; Win98; en-US; rv:0.9.2) Gecko/20010725 Netscape6/6.1"
Platform	Included in User-Agent	navigator.platform	The local OS, e.g., "Win64"
Screen characteristics	N/A	window.screen.*	Information about the local display, e.g., the dimensions and pixel depth
Host	Host	location.host	Specifies the virtual host and port number to use
Referer	Referer	document.referrer	The URL of the page whose link was followed to generate a request for the current page
Origin	Origin	location.origin	Like Referer, but only includes the origin part of the referring URL
Last modified	Last-Modified (response)	document.lastModified	Set by the server to indicate the last modification date for the returned resource
Cookie	Cookie (request), Set-Cookie (response)	document.cookie	A text string containing "key=value" pairs

Overview


prefetch library
1. Load the page
First-party content provider
2. Path constraint tree
Third-party Oblique analysis server
Offline
Online
3. Page + prefetch library
6. Prefetch URLs
https://foo.com
4. page request
First-party web servers
Client browser
5. Page with path constraint tree & prefetch library

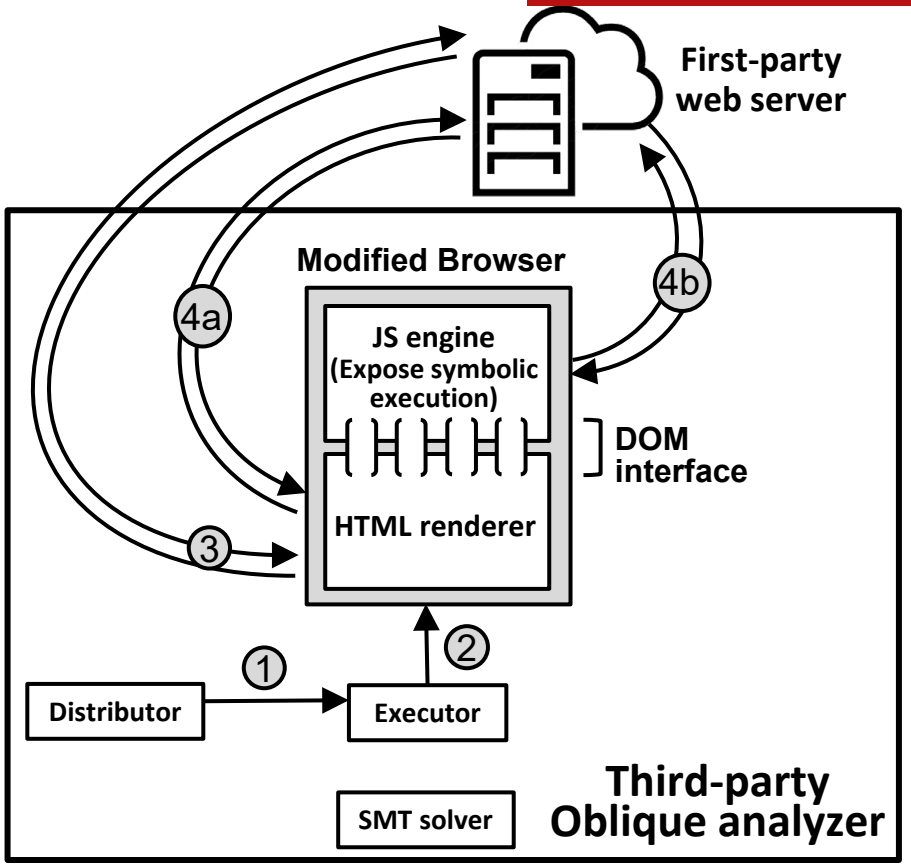
Oblique's Offline Analysis

- High-level goals:
  - Explore all of the execution paths that a page's JavaScript might take, given all possible values for client-specific state like cookies
  - For each path, identify the URLs that the page fetches
- To find these paths, Oblique uses concolic execution

Symbolic Analysis (Concolic Execution)

1. Distributor generates initial concrete values for client symbols (e.g., `Cookie= "cat=yes"`, `User-Agent="MobileChrome"`).
2. Executor launches a web browser
3. Browser fetches concrete page HTML from the first-party web server
4. Browser fetches more concrete URLs
   a. CSS and images handled as normal
   b. JavaScript executes code **concolically** (i.e., concretely + symbolically)

As JavaScript executes on concrete data, Oblique tracks symbolic path constraints and symbolic URLs!



Symbolic Analysis (Concolic Execution)

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2. Executor launches a web browser
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4. Browser fetches more concrete URLs
   a. CSS and images handled as normal
   b. JavaScript evaluated using symbolic execution

As JavaScript executes on concrete data, Oblique tracks symbolic path constraints and symbolic URLs!

[Example of Concolically Executed JavaScript Code]

```
var baseUrl = "foo.com/";
var rndId = Math.random().toString();
if(document.cookie.indexOf("cat")==0){
   fetch(baseUrl + rndId + "/cat.jpg");
}else{
   fetch(baseUrl + "/dog.jpg");
}
```

Concrete URL: `foo.com/0.3274/cat.jpg`

Symbolic URL: $\texttt{foo.com/\{\{rnd}_0\texttt{\}\}/cat.jpg}$

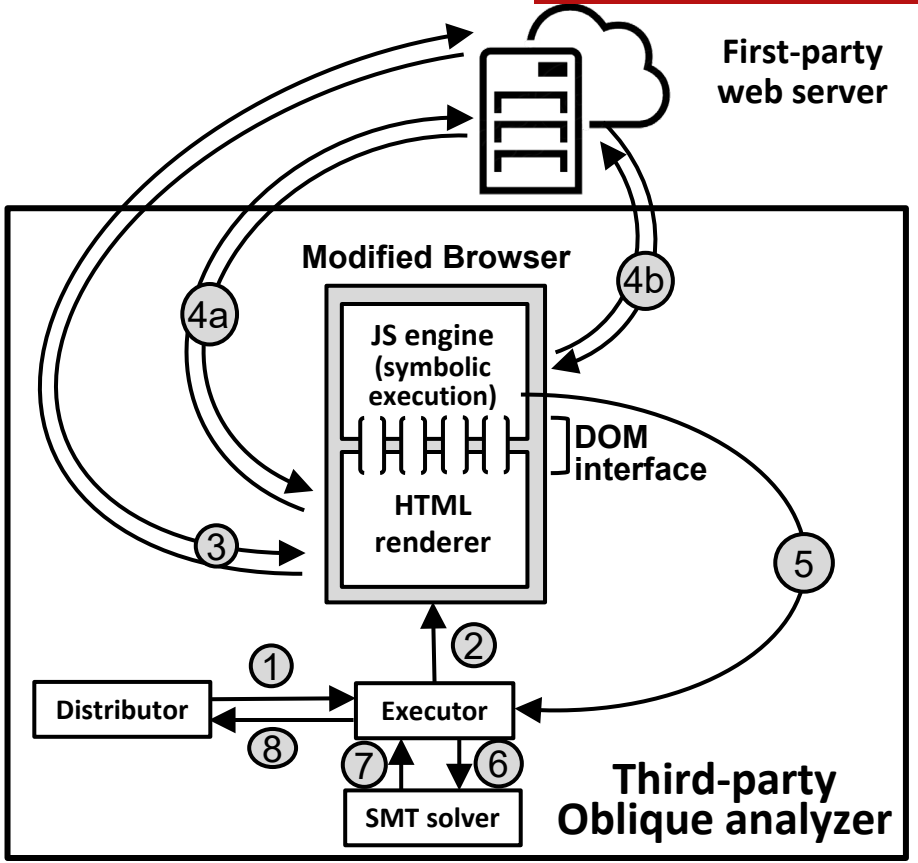
Symbolic path constraint:

`document.cookie == "cat"{{.*}}`

Symbolic Analysis (Concolic Execution)

5. Once the page load finishes, the symbolic path constraint, e.g. `document.cookie = “cat”{{.*}},` is sent to executor
6. Executor asks the SMT solver to invert part of the path constraint, e.g., `document.cookie = ^(“cat”{{.*}})`
7. Solver finds a concrete input that satisfies the inversion, e.g., `document.cookie = “x81b5”`
8. Executor returns the new test input to the distributor, who inserts the input into a priority queue

Repeats Steps 1 - 8



[The Page's JavaScript Code]

```
var baseUrl = "foo.com/";
var rndId = Math.random().toString();
if(document.cookie.indexOf("cat")==0){
   fetch(baseUrl + rndId + "/cat.jpg");
}else{
   fetch(baseUrl + "/dog.jpg");
}
```

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[Path constraint tree + prefetch library]

Client's Cookie: "cat=OfCourse; id=42"

document.cookie == "cat"{{*}}

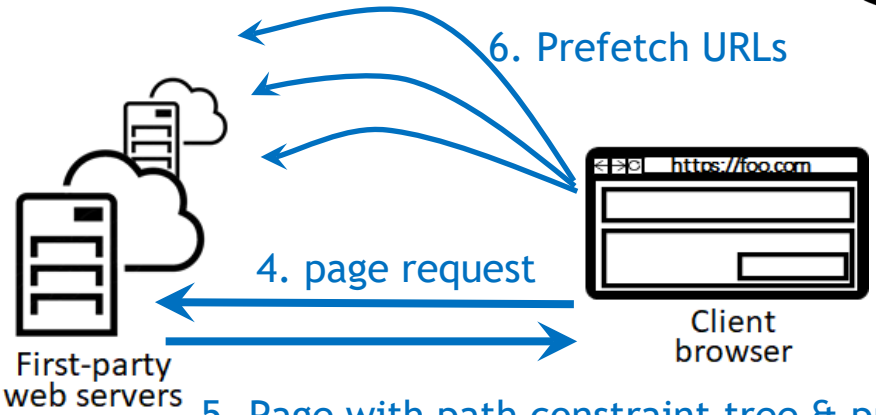
Yes

No

foo.com/{{rnd$_0$}}/cat.jpg

Client generates a random number on-the-fly and then prefetches the concretized URL!

foo.com/dog.jpg

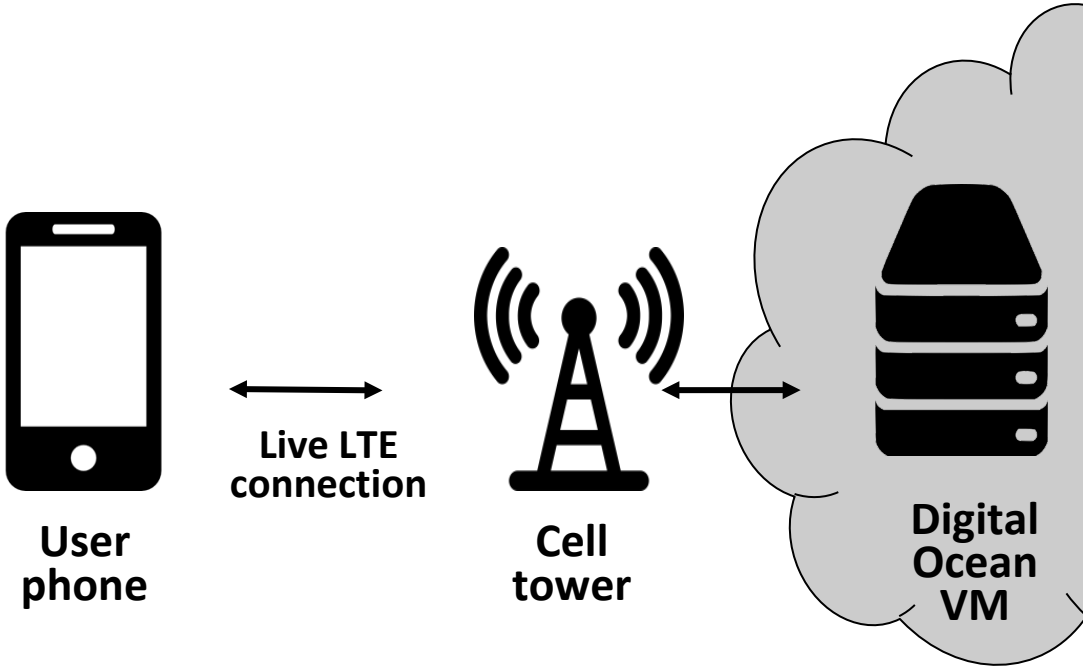


Limitations of Oblique

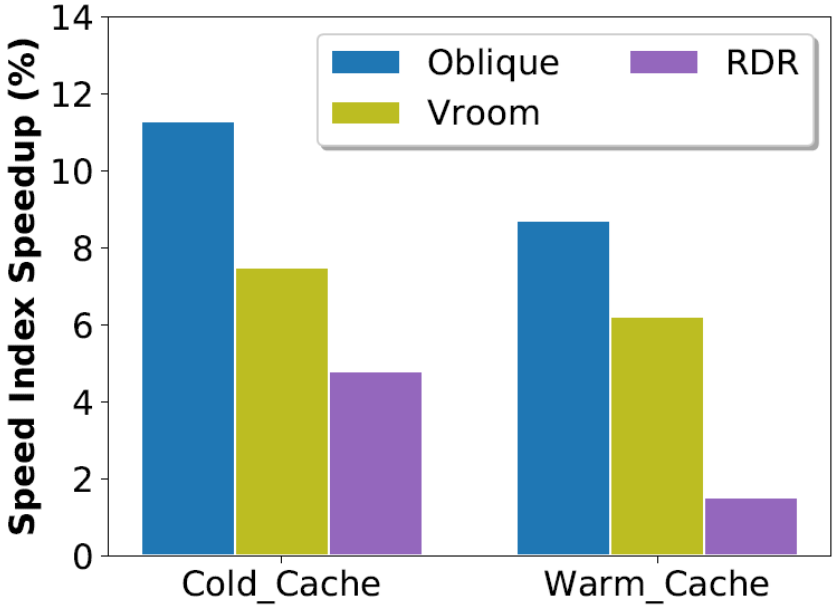
- Only certain native methods are modelled
  - For example, Oblique has a Z3 expression model for `String.charAt()`, but not `Intl.DateTimeFormat()`
  - If the JavaScript string variable `s` contains symbolic data derived from `User-Agent`, then the return value of `String.charAt(s)` will properly capture that symbolic data
  - In contrast, Oblique always treats `Intl.DateTimeFormat(s)` as fully concrete, possibly hurting path coverage
- Oblique's symbolic analysis may time out, hurting path coverage
- Oblique's symbolic analysis can't issue HTTP requests that are nonidempotent

Evaluation Setup

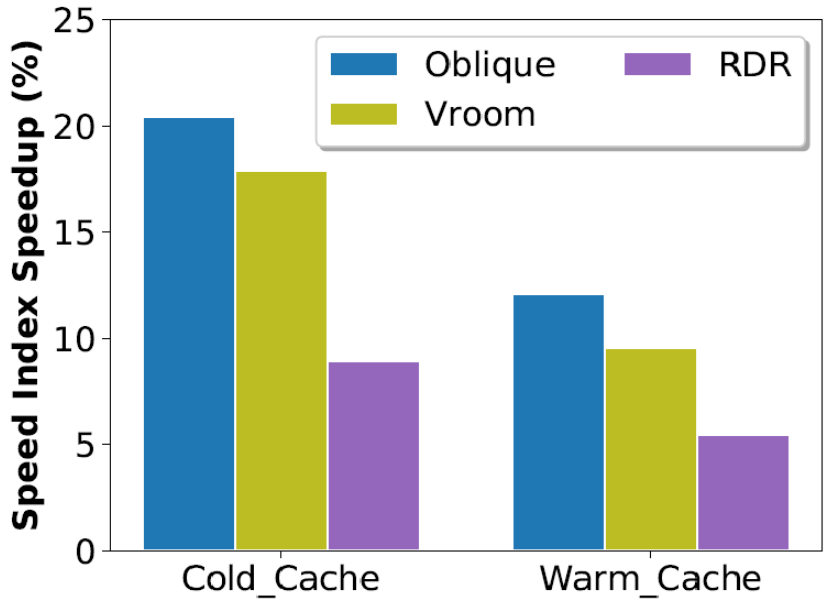
- An HTTP record-and-replay tool recorded content from 200 popular pages
- Digital Ocean VM ran:
  - Oblique web server
  - Vroom server
  - RDR server
- Client device was a Galaxy S10e phone running Chromium v78
  - End-to-end RTT b/w phone and Digital Ocean VM was ~47ms
  - We used `netem` to inject added latency in some experiments



Results: Speed Index

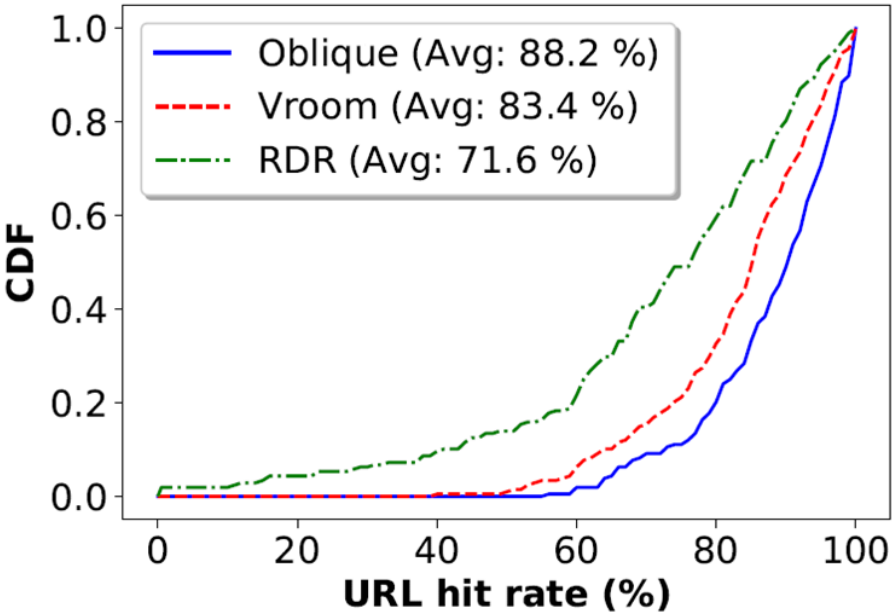


Speed Index (47 ms RTT)

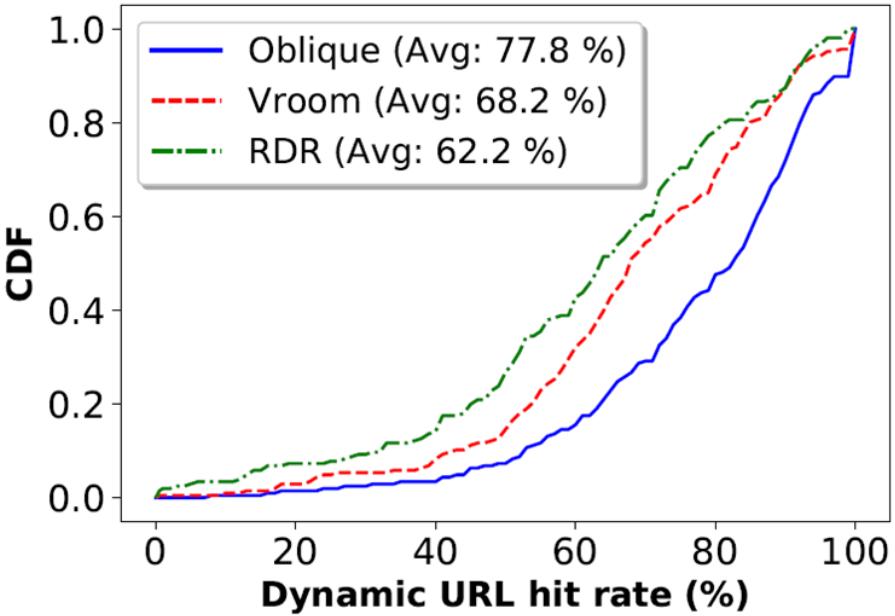


Speed Index (150 ms RTT)

Results: Prefetch Hit Rate



(a) Prefetch hit rate (static+dynamic URLs)



(b) Prefetch hit rate (only dynamic URLs)

Conclusion

- Prefetching helps to reduce page load times
- Prior systems generate URL prefetch lists by:
  - Breaking TLS integrity, or
  - Running first-party analyses that cannot be outsourced
- Oblique uses symbolic execution to eliminate the design tension
  - Oblique's third-party server can model user-specific data as symbols
  - Symbols are only resolved by clients!
- Oblique reduces page loads by up to 31%, outperforming Vroom and RDR by up to 17%

THANK YOU

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