An Overview of Security & Privacy in Content-Centric Networking (NDN and CCN)

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Current Research Topics

- Security of Embedded Devices (IoT?)
- Private Set Operations
  - Cloud/DB apps
  - Genomic S&P
  - Input size-hiding
- Privacy in Social Networks
- Usable Security
- Weird Biometrics
- S&P in CCN/NDN

For more info see: **sprout.ics.uci.edu**

OUTLINE

- Internet
- NDN/CCN Overview
- NDN Security & Privacy
- Anonymous Retrieval
- Cache Privacy
- Denial of Service
- Trust Management
- Optional Topics, e.g.,
  - Access Control, Accounting, Fragmentation, NACKs

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NEED TO KNOW

- Basic networking & Internet concepts
- Network security principles
  - Protocols
- Basic knowledge of applied cryptography
  - Basic crypto primitives

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Today's Internet

- Tremendous, unexpected and long-lasting global success story
- 35-year-old design: architecture defined in RFC 791/793 (1981 and earlier)
- Enables any host to talk to any other host
  - Names boxes and interfaces
  - Supports end-to-end conversations
  - Provides unreliable packet delivery via IP datagrams
  - Compensates for simplicity of IP via complexity of TCP

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IP-Based Internet

- Helped facilitate today's rich global-scale communication
- But, was not designed for it
- Fundamental communication model: point-to-point conversation between two hosts (IP interfaces)
- The central abstraction is a host identifier corresponding to an IP address

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Recent Decades

- Last 20 years – profound change in nature of Internet communication
  - From email/ftp/telnet to what?
  - From a few thousands of users to that?
  - From static wired nodes (computers, terminals) to what?
  - From friendly, clubby, trusting ambience, to what?
- Massive amounts of data constantly produced and consumed
  - Web (esp. media sharing and social networking),
  - Audio-/video-conferencing
  - Email, etc.

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Key Aspects of Internet Change

- Multimedia
- Mobility / Wireless-ness
  - Delays and Disruptions
- Distribution Scale
- Cloud

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Internet Security & Privacy

- S&P in the current Internet are certainly **NOT** a success story
- Retrofitted, incremental, band-aid-style solutions, e.g.:
  - SSH,
  - SSL/TLS,
  - IPSec + IKE,
  - DNSSec,
  - sBGP,
  - AAA, etc.

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NSF Future Internet Architectures (FIA) Program

- Targeted NSF-funded program, 2-tiered competition
- Major goals:
  - Design comprehensive next-generation Internet architectures
  - Accommodate current and emerging comm-n paradigms
  - Security and privacy from the outset (by design)
- Started in 2010
  - Phase I: 2010-2014
  - Phase II: 2014-2018
- Projects:
  - Nebula (Phase I)
  - MobilityFirst (Phases I an II)
  - XIA: eXpressive Internet Architecture (Phases I and II)
  - NDN: Named-Data Networking (Phases I and II)
  - ChoiceNet (started in 2012, not strictly speaking FIA)

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Caveat Emptor

- I was part of the NDN FIA project 2010-2014
- Worked on S&P in NDN (and CCN)
- Was funded by the NSF ('till 09/15)
- Thus… take everything with a grain of salt, draw your own conclusions, and explore further

Also:

- I focus on NDN and CCN
- There are other ICN efforts

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- "Named data networking project (NDN)", http://named-data.org
- "Content centric networking (CCNx) project", http://www.ccnx.org
- "Networking named content", ACM CoNEXT, 2009.

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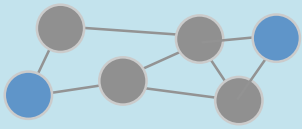
Communication

- For almost 150 years, communication meant:
  A wire connecting two devices



- The Web forever changed that:
  What matters is content, not the host it came from

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DN vs. CN

	Communication	Distribution
Naming	Endpoints	Content
Memory	Invisible, Limited	Explicit; Storage = Wires
Security	Communication process	Content

Today's Internet: a communication network, used as a distribution network

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Named-Data Networking (NDN)

✧ An instance of ICN and CCN

<u>NDN focuses on:</u>
Scalable Content Distribution which is poorly served by today's Internet

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NDN: key participants

THE UNIVERSITY OF MEMPHIS
Northeastern University
Colorado State University
parc A Xerox Company
ARIZONA
Washington University in St. Louis
UCSD
UCIRVINE
University of Colorado Boulder
UCLA
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
UNIVERSITY OF MARYLAND 1856

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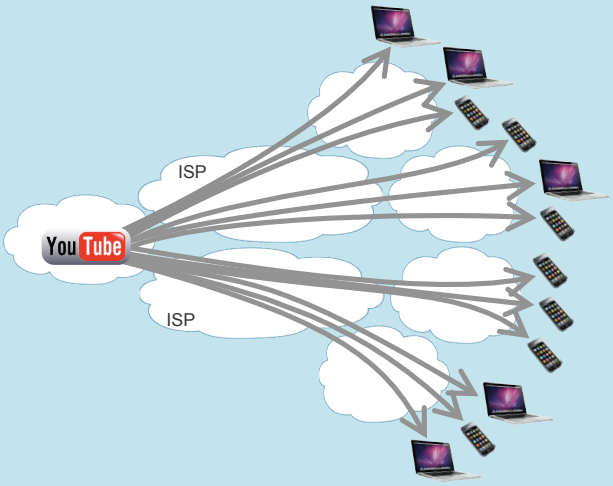
Content Distribution over IP



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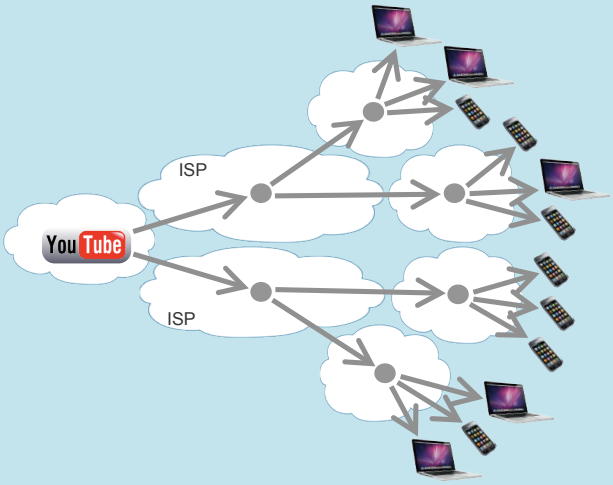
Content Distribution over NDN



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NDN Basic Concepts

- Name
  - Human-readable, path/url - like
- Roles:
  - Consumer
  - Producer
  - Router
- Objects:
  - Content
  - Interest

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As opposed to IP

- Host
- Interface address (IP address)
- Datagram/Packet
- Router

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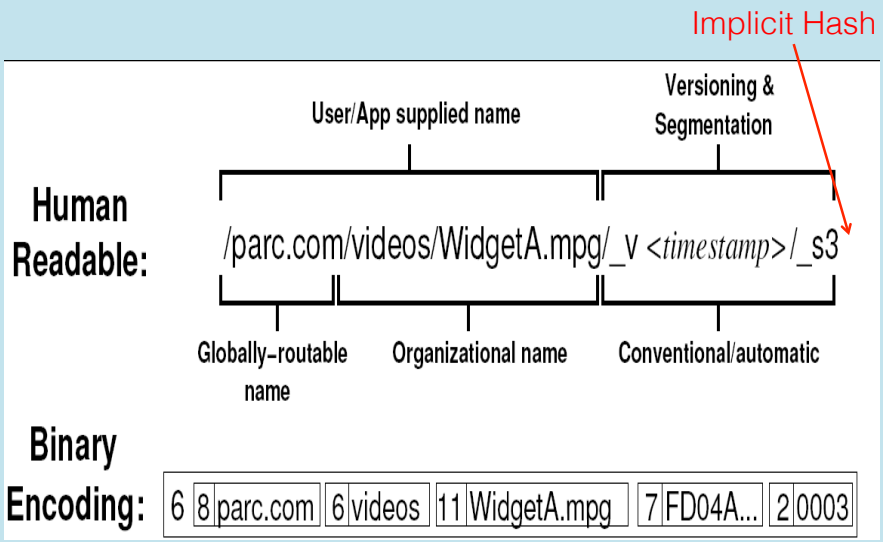
Name Structure



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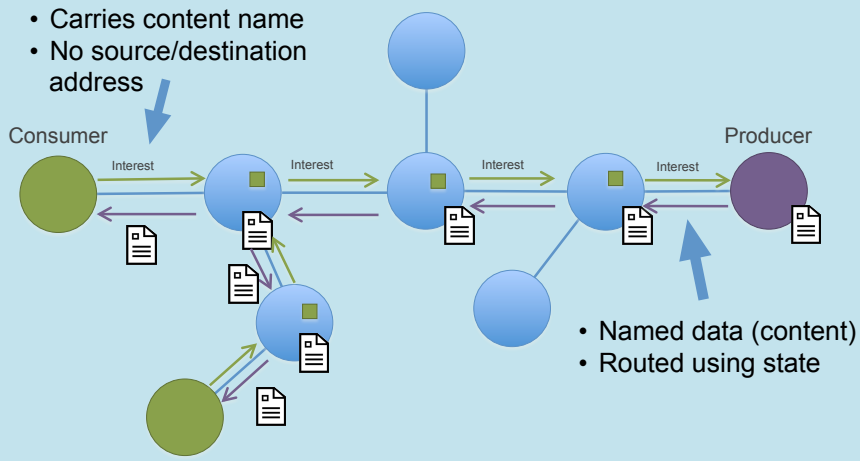
How NDN works
(abbreviated version)



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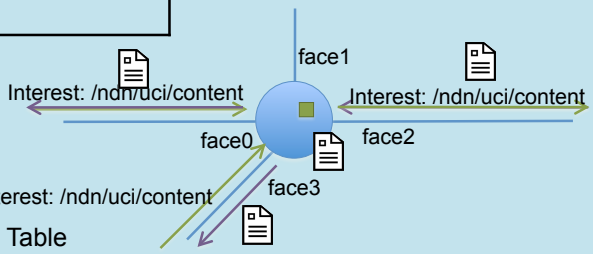
Zooming In:

Interest	Incoming face
/ndn/uci/content	face0, face3

/ndn/uci/content



Every router has a:

- PIT: Pending Interest Table
- CS: Content Store (Cache)
- FIB: Forwarding Information Base

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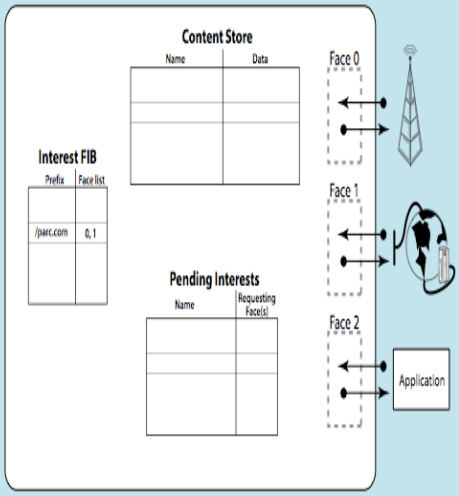
Forwarding

- Main operation is prefix-based longest match lookup, like IP
- Interests forwarded according to routing table, but multipoint forwarding, broadcast, local flooding are all okay
- Data follows interest path in reverse



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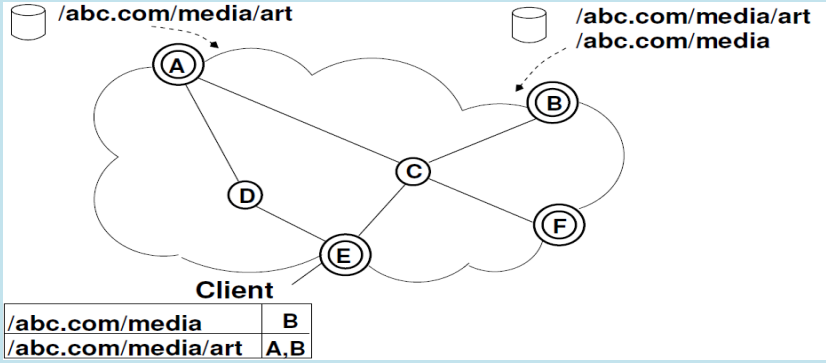
Routing

- Routing based on name prefixes + reachability, like IP
- Can reuse IP routing protocols, e.g., IS-IS, BGP



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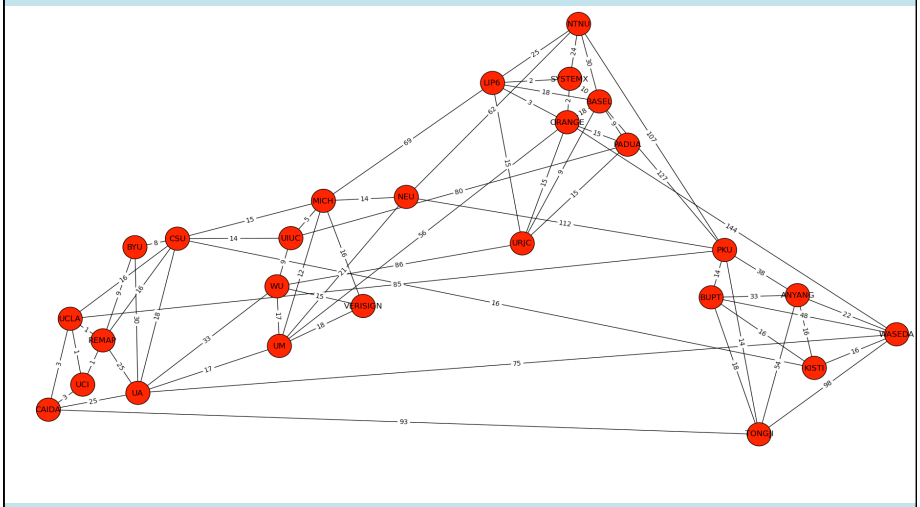
NDN Testbed



Live demo: www.arl.wustl.edu/~pcrowley/NDN_GEC13_demo.mp4

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Security

- **Now**: secure the pipe
  - Data is authentic because it emanates from the right box (which is an end-point of the right secure pipe)
- **NDN:** Integrity and trust as properties of content
  - Should be inferred from content itself

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Securing Content: how?

Current SSL/TLS 3-way handshake model is not a good fit for NDN:

- Secures channel, not data
- Authentic content can come from anywhere
- But, access control (and accounting) is difficult
- After content retrieved from origin, it's served by the network (from caches)

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Authenticity of Content

Content can be retrieved from anywhere by any consumer

- How can it be trusted?
- How do we know who produced it?
- How do we know it is the right content?

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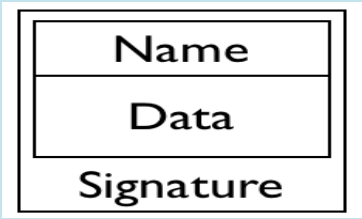
Securing Content

NDN Content object:



- **Integrity**: is data intact and complete?
- **Origin:** who asserts this data is an answer?
- **Correctness:** is this (content) an answer to my question (interest)?
- **Bonus feature**: routers can choose to verify content (with caveats)

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Private Content

Access to content can be restricted, e.g.:

- Encrypt once with a symmetric key
- Symmetric key distributed using “standard” techniques (pigeons?)
- Access control on key rather than content
    - This can make long-term secrecy problematic

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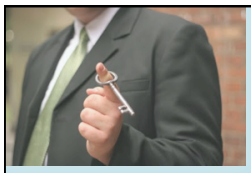

Trust Model?

- All content is signed
- Interests are not…
- NDN is PKI-agnostic
- Application-specific vs network-layer trust

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NDN: Privacy Benefits

- Interest has no source address/identifier
- Content can be routed without knowing consumer identity and/or location
- One observed interest may correspond to multiple consumers at various locations
- Router caches reduce effectiveness of observers close to producers

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NDN: Privacy Challenges

- Name privacy in interests

  /ndn/us/wikipedia/STDs/herpes

- Name privacy in content

  /ndn/zimbabwe/piratebay/XSOQW(#E@UED$%.mp3

- Signature privacy
  - Leaks content publisher identity
  - Classical privacy vs. security conflict
- Cache privacy
  - Detectable hits/misses

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NDN: Security Benefits

- Simplicity
- All content is signed
- No need for security handshakes in real time
- A producer's public key is a type of content
  - Pull PKC first, then request content

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NDN: Security Challenges

- State in routers is both a blessing and a curse
- Any such state can be abused
- DoS attacks:
  - Interest Flooding
  - Content Poisoning: proactive & reactive
- Covert Channels & Geo-location
- Content Access Control
- Trust management at the network layer

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NDN: quick recap

PRODUCER

- Announces name prefixes
- Names and signs content packets
- Injects content by answering interests

CONSUMER

- Generates interest packets referring to content by name
- Receives content, verifies signature, decrypts if necessary

ROUTER

- Routes interests based on (hierarchical) name prefixes – inherently multicast
- Remembers where Interests came from (PIT), returns content along same path
- Optionally caches content (in CS)
- May verify content signatures

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Some Recent & Ongoing Work

- Anonymous content retrieval
- DoS/DDoS defense:
  - Content poisoning countermeasures
  - Interest flooding mitigation
- Privacy in Router Caching
- Covert channels and Geolocation
- Secure content fragmentation
- NDN security in non-distributive settings
  - Instrumented Environments (actuation/control)
  - Sensor Networks
  - Bidirectional low-latency communication
- Trust Management
- Fragmentation
- Accounting
- Content Deletion
- Negative Acknowledgments
- Access Control
- Key Name Service (PK Discovery)
- Private Content Retrieval

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Why Name Privacy?

NDN names are expressive and meaningful, but…

- Leak information about requested content
- Easy to filter/censor content, e.g., block everything like:

/ndn/cnn/world-news/russia

However:

- NDN names are opaque to the network
- Routers only need to know name component boundaries – "/"
- Names can carry binary data

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ANDaNA: Anonymous Named Data Networking Application

- Observers close to consumer should not learn what content is being requested
- Target: low-to-medium-volume interactive communication
- Producers might not be aware of ANDaNA

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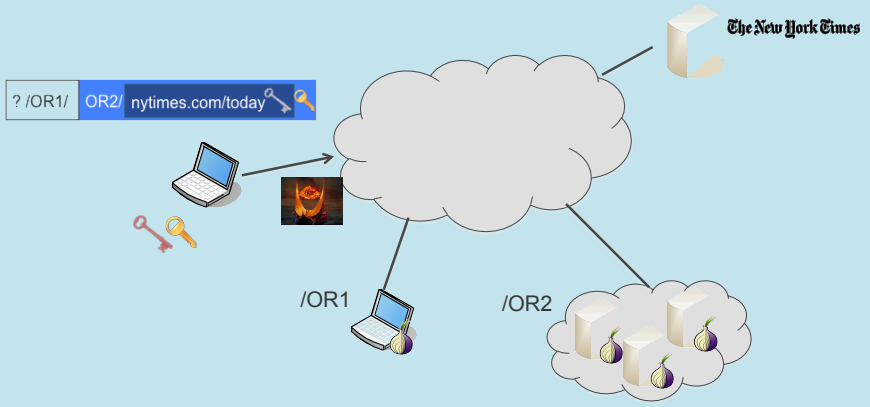
[DGTU-NDSS2012]

ANDaNA



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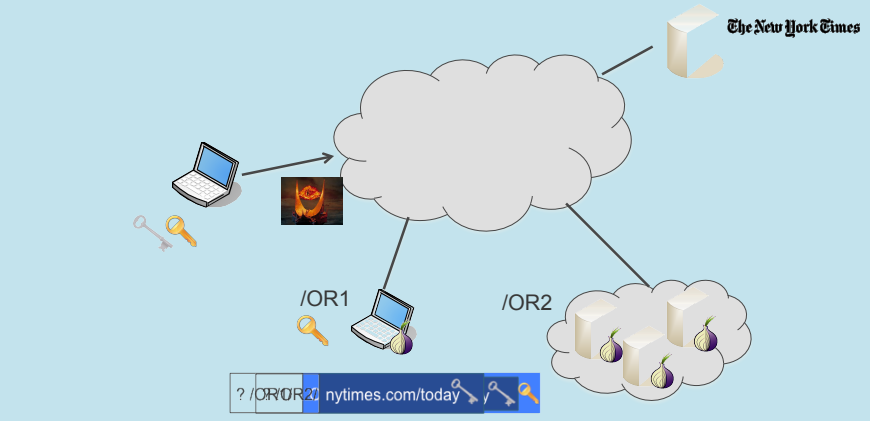
ANDaNA



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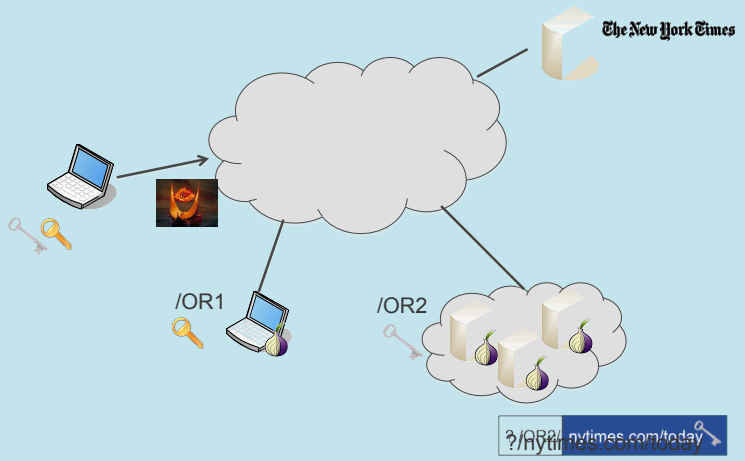

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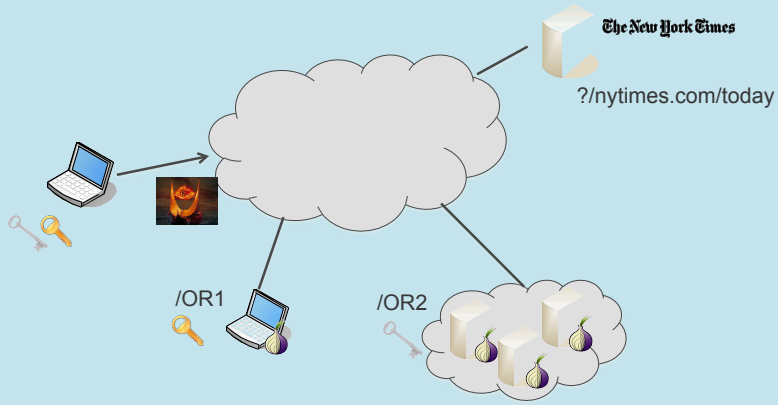

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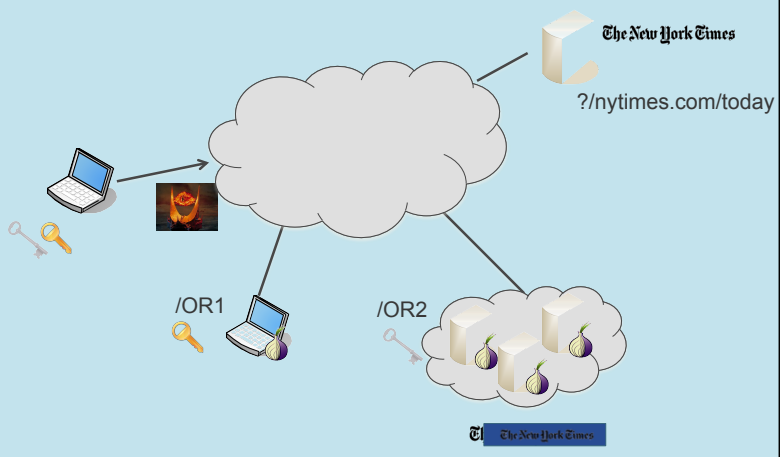

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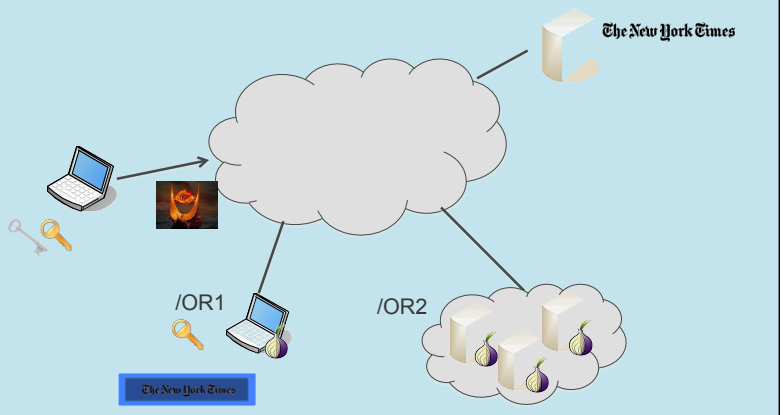

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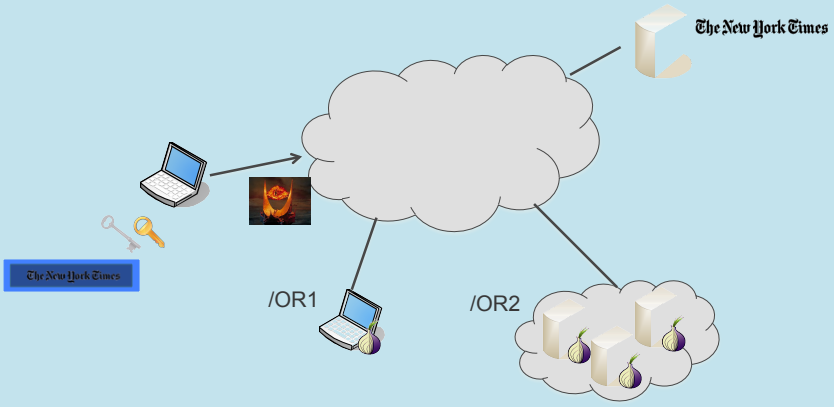

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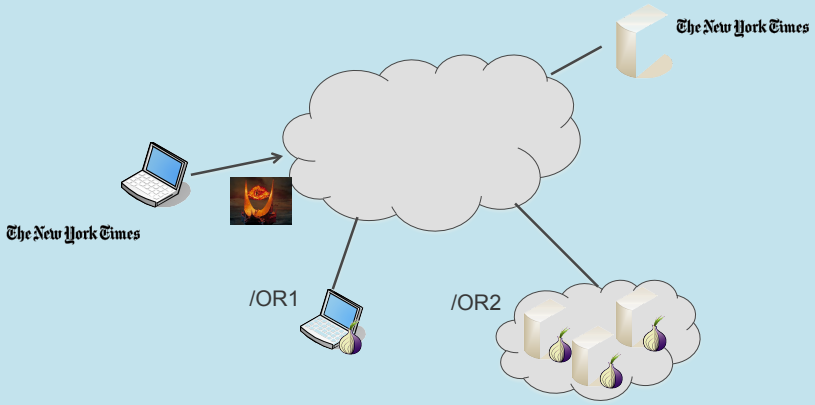

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ANDaNA

Privacy with 2 hops comparable to Tor with 3

- Why? Lack of source address in interests
- Anonymizing routers do not learn origin of traffic (only the previous hop)
- Lower overhead

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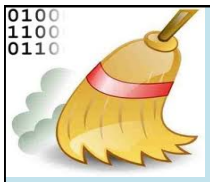

NDN Cache Privacy

- Router Caching is good for performance
  - Better bandwidth utilization
  - Lower latency
- But… bad for privacy
  - Timing attacks
  - Cache harvesting attacks

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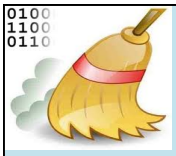

Cache Privacy

- Who could the adversary be?
  - Another host or router
  - A malicious application on victim's device
- Where could the adversary be?
  - Near consumer, e.g., on the same LAN/WLAN segment
  - Near producer (opposite sides of first hop router)
  - In both places at once

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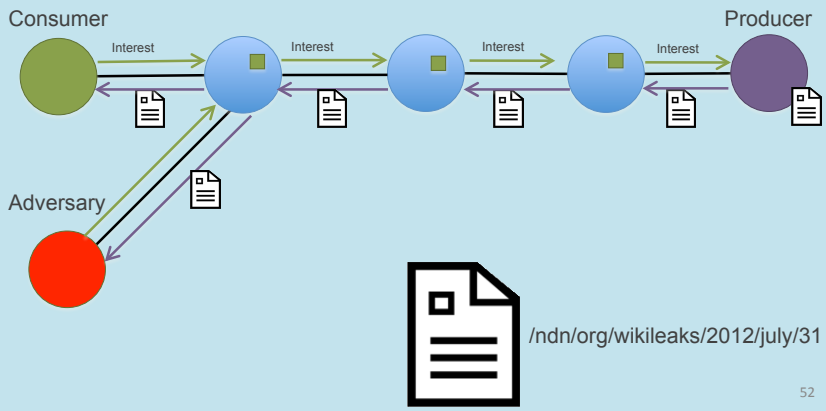
Scenario 1: Victim=Consumer



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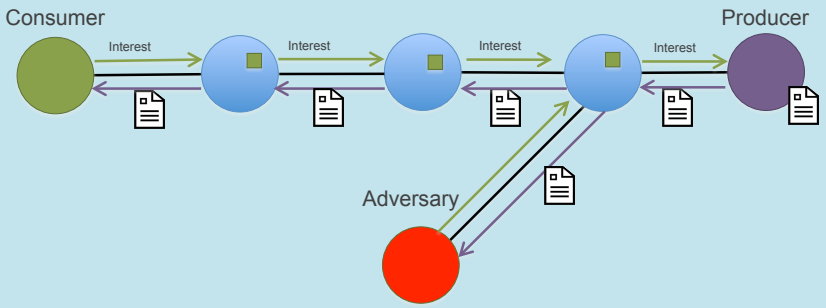
Scenario 2: Victim=Producer



/ndn/org/wikileaks/2012/july/31

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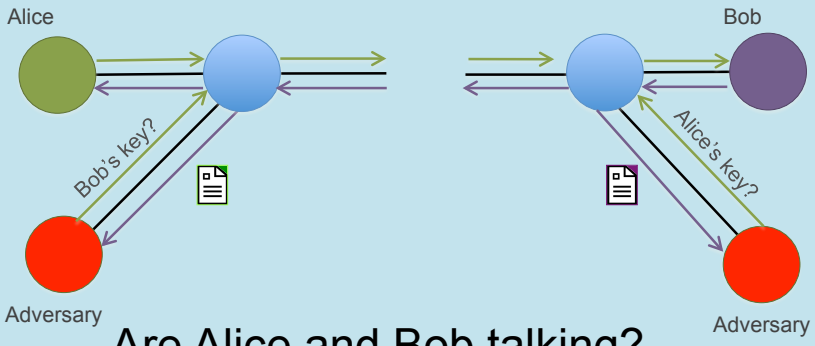
Scenario 3: Victims=Both



Are Alice and Bob talking?

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Countermeasures

- Do not cache content at all
  - Bad idea…
- Cache and delay
  - Which content? Who decides?
  - How long to delay?

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Countermeasures

- Two types of traffic:
  - Private
  - Non-private
- Two communication types:
  - Low-latency (interactive) traffic
    - Use unpredictable content names
  - Content distribution traffic; details in paper, IEEE ICDCS'13
    - Random delay
    - Content-specific delay
- Introduce a privacy bit in interests and/or content?

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DoS/DDoS in NDN

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DoD/DDoS Resistance?

Some current DoS + DDoS attacks become irrelevant in the NDN architecture

- Content caching mitigates targeted DoS
- Content is **not** forwarded without prior state set up by interest(s)
- Multiple interests for same content are collapsed
- Only one copy of content per “interested” interface is returned
- Consumer can’t be “hosed” with unsolicited content

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DoS/DDoS

- Attacks on infrastructure
  - Loop-holing/black-holing
  - Interest flooding
  - Router resource exhaustion
- Attacks on Consumers + router caches
  - Content flooding
  - Cache pollution
  - Content/cache poisoning

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Interest Flooding

Adversary generates numerous non-sensical interests, e.g.:

/ndn/us/ca/uc/uci/cs/gene.tsudik/random-string

Any legitimate producer prefix

- Guaranteed to reach the producer
- Consumes precious router resources (PIT entries)
- IF attack affects both routers and producers

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Interest Flooding

Potential countermeasures:

1. Unilateral rate limiting/throttling
   - Resource allocation determined by router state
2. Collaborative rate limiting/throttling
   - Routers push back attacks by interacting with neighbors

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Content Poisoning

1. Adversary is on the path to producer (e.g., a router)
   - Intercepts genuine interest, replies with fake content
   - Content settles in routers
2. Adversary is NOT on the path to producer
   - Anticipates demand for content
   - Issues own interest(s), replies with fake content
   - Content settles in routers

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Content Poisoning

Potential countermeasures:

- Signature verification in routers?
- Consumer feedback?
- AS egress router verification only?

BTW: what is "fake" content?

- Bad signature (fails verification) ,
- Bad signing key

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Content Poisoning Mitigation

- NDN objective is content distribution
- Facilitated by caches + PITs in routers

- Consumer must verify content signatures
- But … how to flush fake content from router caches?
- NDN allows exclusion filters in interests (by hash)
  - Can be used, with very limited efficacy
  - Immediate flush: DoS
  - Verifying signatures: expensive + another DoS type
- Consumer authentication contradicts interest opacity

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Public Keys in NDN

- A public key is a type of content, i.e., a certificate
- Contains authorized name prefixe(s):
- For example:

  /cnn/usa/web/key

OR

  /verisign/europe/key

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Content Poisoning

Two reasons:

- Ambiguous interests
- No unified trust model: applications are diverse and dynamic

AXIOM: Network-layer trust and content poisoning are inseparable

Routers should do minimal work:

- Not verify/fetch public keys (except for routing)
- Do bounded, fixed amount of work per content
  - e.g., verify at most one signature

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Interest-Key Binding Rule (IKB)

IKB (general): An interest must reflect the trust context of the consumer's application, thus making it (easily) enforceable at the network layer

IKB (NDN/CCN): An interest must reflect the public key of the content producer

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Interest-Key Binding Rule (contd.)

IKB (NDN/CCN): An interest must reflect the public key of the content producer

- Make `PublisherPublicKeyDigest` (PPKD) field mandatory in every interest
- Consumers obtain and validate keys, using
  - Pre-installed root keys
  - Key Name Service (KNS)
  - Global search-based service

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Interest-Key Binding Rule (contd.)

- Producer:
  - Includes public key in each content's `KeyLocator` field
- Router:
  - Matches `KeyLocator` digest to PPKD in PIT
  - Verifies signature using `KeyLocator`
  - **No fetching, storing, parsing of public keys**

  → Note: PIT entry collapsing takes PPKD into account

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Is this Secure?

CLAIM:
Adherence to IKB ➔ security against content poisoning

- Assume:
  - All nodes abide by IKB
  - Consumer not malicious
  - Consumer-facing routers – not malicious
  - Consumer←→first-hop router link not compromised

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Is this Secure?

- Consumer sends interest containing PPKD
- Router ensures that:
  - Valid content signature using key in `KeyLocator`
  - Digest of `KeyLocator` matches PPKD in PIT
- Consumer-facing router not malicious ➔ only possibility of poisoned content is **hash collision**

- If upstream malicious routers send fake content:
  - Consumer-facing router detects and drops it

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Optimizations

- Include keys in interest:
  - ✓ Save storage
  - x Requires changes to interest & content structure

- Only AS border routers implement IKB
  - ✓ Better performance
  - x Possible attacks within AS
    But … detectable by border routers

  NOTE: each router must at least do a PPKD match

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Optimizations (contd.)

- Self-Certifying Name (SCN)
  - Hash of content (including name) as last component of name
- Benign consumers use SCN ➔ network delivers "valid" content
- **No** signature verification by routers:
  - Only one hash re-computation
- How to get content hash in the first place?

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Catalogs and SCN-s

A catalog:
- An authenticated (signed) data structure
- Contains one or more SCN-s, nesting arbitrary
- Any authenticated data structure
  - Hash chains, MHTs, skip-lists, etc.
- Structure is application-specific
- Use IKB to bootstrap (fetch catalogs)

- SCN obtained from a catalog:
  - ✓ **No** signature verification by routers/consumers
  - ✓ **No** need to sign content by producers

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Two types of traffic

1. Content Distribution, e.g.:
   - Video streaming:
     - One big catalog containing SCNs of all segments
     - Or, hash chains (with data), or MHT, etc.
   - Fore example, Web browsing:
     - HTML file as a catalog
     - Contains SCN of sub-pages/components
     - Works only for static content

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Two types of Traffic (contd.)

2. Interactive Traffic
   - Content generated on demand (real-time), e.g., audio/video conferencing,
   - Catalogs not viable
   - Content must be requested by setting PPKD in interest

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Content NACKs: what if?

- Consumer obtains hash H of content C from P's catalog
- Consumer generates interest for C referring to H
- But, C is no longer available at P
- P receives interest and ???
  - Drops it – bad for Consumer

  Or:
  - NACK-s it – routers will drop the NACK since a NACK's hash doesn't match H

Bottom-line: need to augment iKB and interest format to allow for SCN-carrying interests to still refer to P's public key.

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Fragmentation

- Internet connects heterogeneous devices over heterogeneous links, with different:
  - Physical layers (copper, fiber, radio, laser)
  - MAC layers
  - Maximum Transmission Unit (MTUs)
    - Determined by MAC layer

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Fragmentation

- Fragmentation: splitting a packet into fragments that fit into outgoing link MTU
  - Fragment header encodes ordering of related fragments
  - Re-fragmentation can occur if smaller MTU is encountered

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Fragmentation – IPv4

Src IP	Dst IP	Len=4000	ID=x	MF=0	Offset=0	Data

Src IP	Dst IP	Len=1500	ID=x	MF=1	Offset=0	Data
Src IP	Dst IP	Len=1500	ID=x	MF=1	Offset=185	Data
Src IP	Dst IP	Len=1040	ID=x	MF=0	Offset=370	Data

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Fragmentation – IPv4

- Issues:
  - Several attacks
    - Ping of death
    - Tiny fragment
  - Router overhead and code complexity
- Results:
  - Deprecated in IPv6 and limited to source-based fragmentation

C. Kent and J. Mogul, Fragmentation considered harmful, SIGCOMM 1987.

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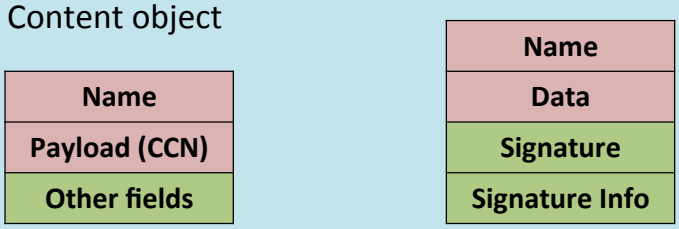
Fragmentation – NDN/CCN

- Two messages types:
  - Interest message
  - Content object



Interest Content

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Interest Fragmentation

- Recall that NDN interests are processed using referenced content name
  - Names can be of arbitrary size
  - Longest-prefix match on a name requires the entire name before performing a search
- Intermediate fragmentation & reassembly for interests is unavoidable

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Content Segmentation

- Segmentation (at source) can avoid fragmentation
  - Data segmented by application
  - Signature computed per segment
- Segments are numbered
  - /youtube/dancingcats/s0
  - /youtube/dancingcats/s1

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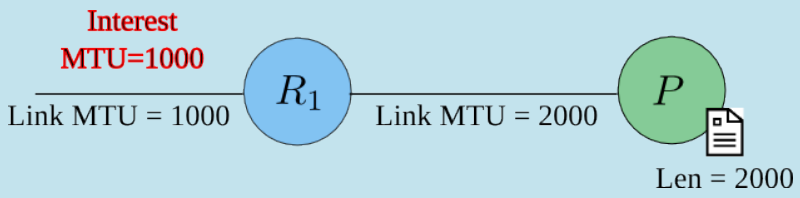
Content Segmentation

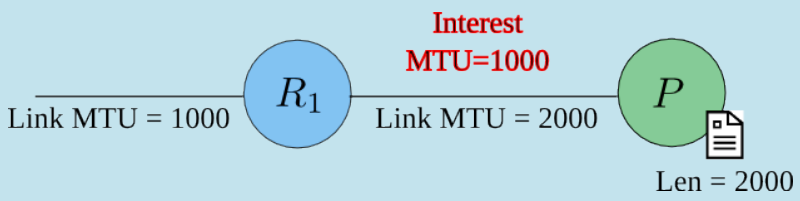
- Use path MTU discovery
  - Mark interests with smallest transmit MTU in a path



85

Content Segmentation

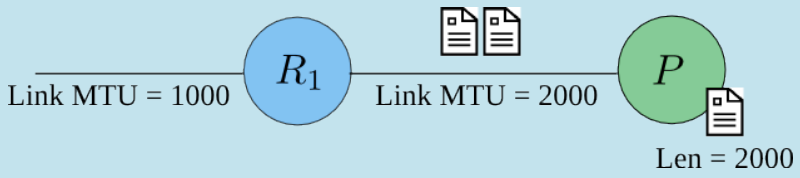
- Use path MTU discovery
  - Mark interests with smallest transmit MTU in a path



86

Content Segmentation

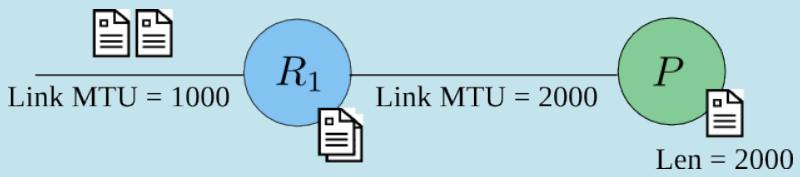
- Use path MTU discovery
  - Mark interests with smallest transmit MTU in a path



87

Content Segmentation

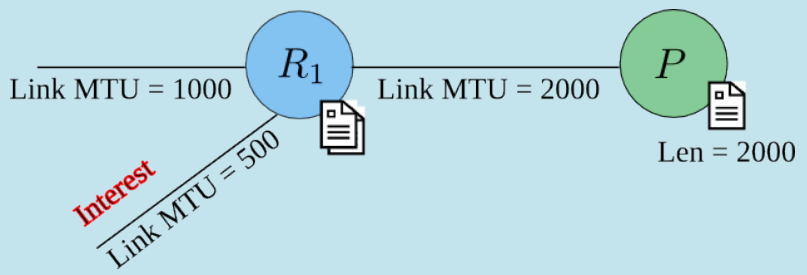
- Use path MTU discovery
  - Mark interests with smallest transmit MTU in a path



88

Content Segmentation

- Use path MTU discovery
  - Mark interests with smallest transmit MTU in a path



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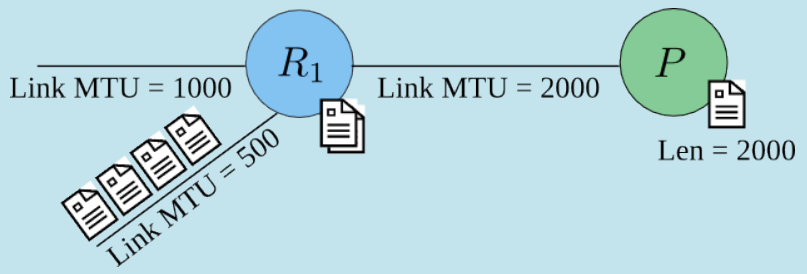
Content Segmentation

- Use path MTU discovery
  - Mark interests with smallest transmit MTU in a path



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Content Segmentation

- Problem
  - Producer cannot segment for all MTUs

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Content Segmentation

- Problem
  - Producer cannot segment for all MTUs

Content Intermediate re-fragmentation is unavoidable

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Content Segmentation

- In CCN/NDN:
  - Routers are not required to verify signatures
  - But… they might

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Content Segmentation

- In CCN/NDN:
  - Routers are not required to verify signatures
  - But… they might

Provide content authentication without intermediate reassembly

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Content Fragmentation

- In today's Internet
  - Packet fragments might not follow same path
- In CCN/NDN:
  - All content fragments follow the same path
  - But… out of order delivery is possible, even between adjacent routers
    - Parallel links with different speeds and/or loss/error

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Content Fragmentation

FIGOA: **F**ragmentation with **I**ntegrity **G**uarantees and **O**ptional **A**uthentication

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Content Fragmentation

- **FIGOA** supports:
  - Cut-through switching & optional intermediate reassembly
  - Security via *Delayed Authentication*
  - Also supports integrity with optional authenticity

97

Content Fragmentation

- **FIGOA** supports:
  - Cut-through switching & optional intermediate reassembly
  - Security via *Delayed Authentication*
  - Also supports integrity with optional authenticity

- Not CCN/NDN-specific
- Works with any network architecture with path consistency guarantees

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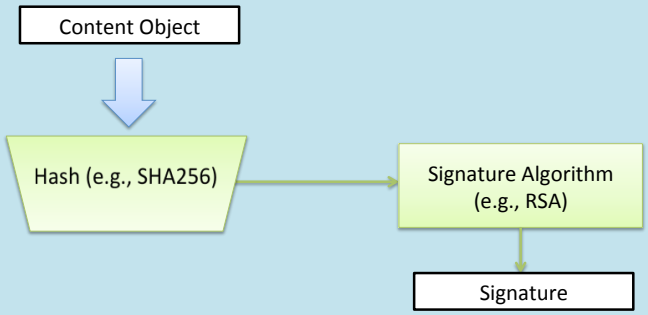
Content Fragmentation

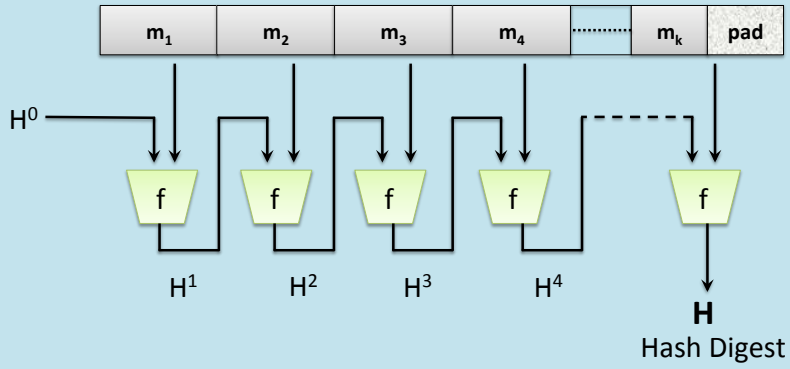
- Hash-and-sign



99

Content Fragmentation

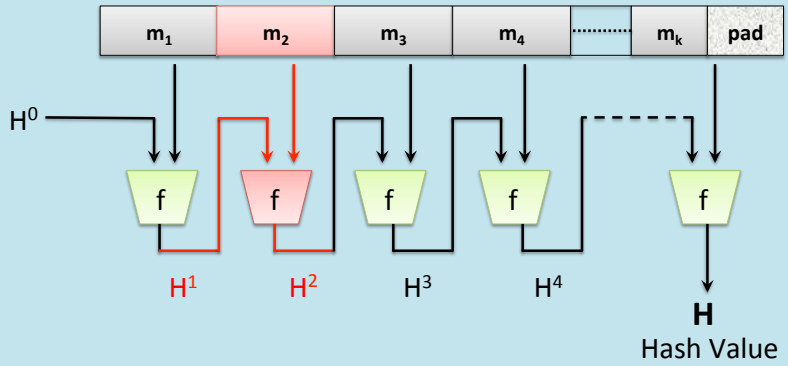
- Merkle-Damgard construction



100

Content Fragmentation

- Merkle-Damgard construction



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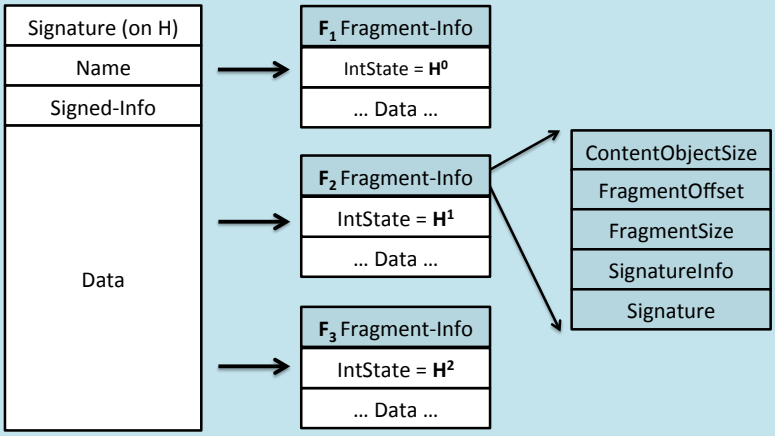
Content Fragmentation



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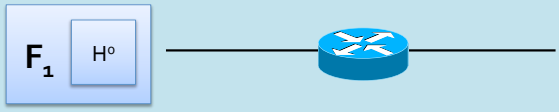
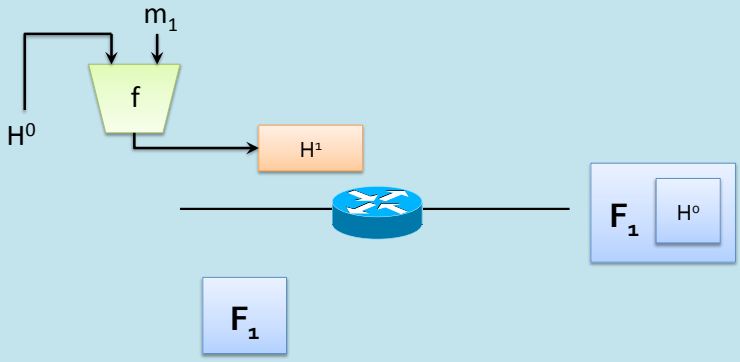
Content Fragmentation



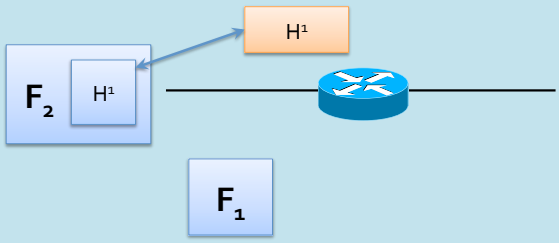
103

Content Fragmentation



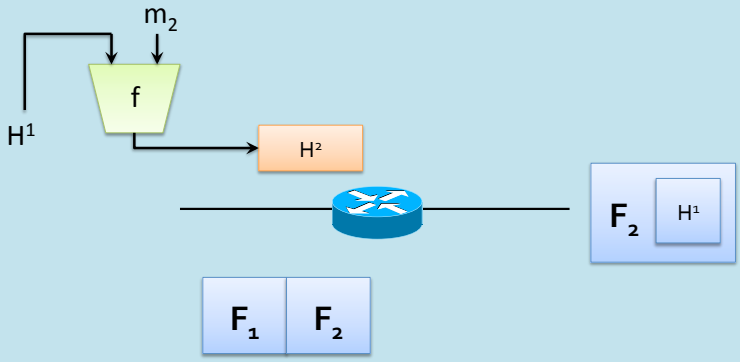
104

Content Fragmentation



105

Content Fragmentation



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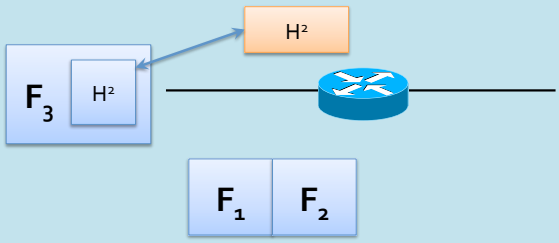
Content Fragmentation



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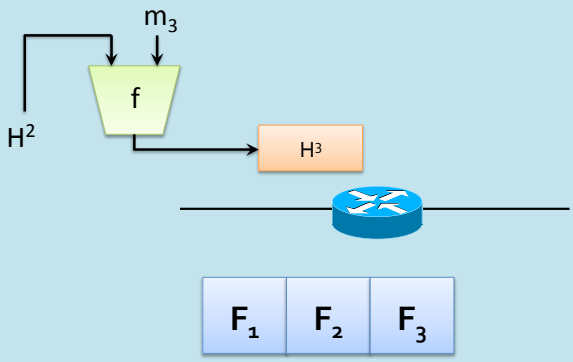
Content Fragmentation



Verify signature (contained in F_3) using H^3

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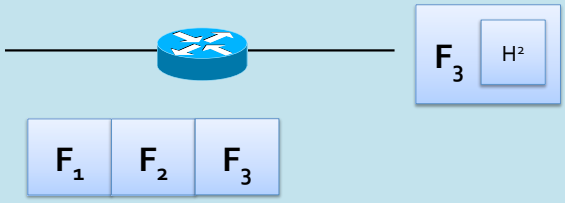
Content Fragmentation



Success

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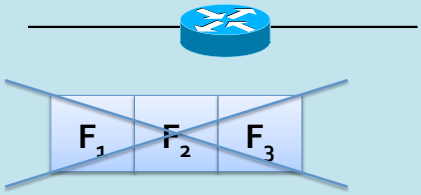
Content Fragmentation



Fail

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Content Fragmentation

- Hash is computed gradually
- FIGOA works with out-of-order fragments
  - F_1 is received → calculate H^1
  - F_3 is received → calculate H^3
  - F_2 is received → calculate H^2
  - Ensure calculated IntState = received ones
  - Verify signature

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Content Fragmentation

- If content is cached:
  - Routers store fragment info, including data
  - Content can be cached fragmented or assembled
- If content is not cached, routers store:
  - Fragments offsets
  - Intermediate state

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Conclusion

- Fragmentation is a must in CCN/NDN
  - Interest
  - Content
- Segmentation does not avoid fragmentation
- Neither does MTU discovery

FIGOA: **F**ragmentation with **I**ntegrity **G**uarantees and **O**ptional **A**uthentication

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NDN S&P References

S. DiBenedetto, P. Gasti, G. Tsudik and E. Uzun,
ANDaNA: Anonymous Named Data Networking Application, NDSS 2012.

J. Burke, P. Gasti, N. Nathan and G. Tsudik,
Securing Instrumented Environments over Content-Centric Networking:
the Case of Lighting Control via Named-Data Networking, IEEE NOMEN 2013.

G. Acs, M. Conti, C. Ghali, P. Gasti and G. Tsudik,
Cache Privacy in Name-Data Networking , IEEE ICDCS 2013.

P. Gasti, G. Tsudik, E. Uzun, and L. Zhang,
DoS & DDoS in Named-Data Networking, IEEE ICCCN 2013.

A. Afanasyev, P. Mahadevan, I. Moiseenko, E. Uzun and L. Zhang,
Interest Flooding Attack and Countermeasures in Named Data Networking, IFIP Networking 2013.

A. Compagno, M. Conti, P. Gasti and G. Tsudik
Poseidon: Mitigating Interest Flooding DDoS Attacks in Named Data Networking, IEEE LCN 2013.

C. Ghali, G. Tsudik and E. Uzun,
Elements of Trust in Named-Data Networking, ACM SIGCOMM CCR, October 2014.

M. Conti, P. Gasti and G. Tsudik,
Exploring Covert Channels in Named Data Networking, AsiaCCS 2014.

A. Compagno, M. Conti, P. Gasti, L. Mancini and G. Tsudik
"Violating Consumer Anonymity: Geo-locating Nodes in Named Data Networking", ACNS 2015.

A. Compagno, M. Conti, C. Ghali and G. Tsudik,
To NACK or not to NACK? Negative Acknowledgments in Information-Centric Networking, IEEE ICCCN 2015.

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