Resilience Despite Malicious Participants

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This talk

- I’ll give a few examples to show the wildly different types of problems and solutions

Byzantine Failures

- Fail-stop: Something works perfectly, then halts
- Byzantine: Where something stops doing the right thing, but doesn't halt, for instance
  - Sends incorrect information
  - Computes incorrectly
- The term came from a famous paper where a bunch of processors try to agree on the value of a bit ("attack" or "retreat")
  - Lamport, L., Shostak, R., Pease, M. (1982). "The Byzantine Generals Problem", *ACM Transactions on Programming Languages and System*
- Misbehavior can cause problems even if not consciously malicious (bugs, misconfiguration, hardware errors)

Malicious Participants

- All sorts of things can be subverted with a small number of malicious participants
  - “How a Lone Hacker Shredded the Myth of Crowdsourcing”
    - https://medium.com/backchannel/how-a-lone-hacker-shredded-the-myth-of-crowdsourcing-d9d0534f1731

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- However…Things that shouldn’t work (but do)
  - Wikipedia
  - Ebay

I’ll talk about different examples

- PKI model resilient to malicious CAs
- Networks resilient to malicious switches
- Resilient and nonresilient designs for data storage with assured delete
- Human

Example 1: PKI

What’s PKI?

- “Public Key Infrastructure”
- A way for me to know your public key

Next topic: Trust Models for PKI

- Where damage from dishonest or confused CAs can be limited

Quick review of public keys, certificates, PKI, CAs

- Certification Authority (CA) signs “Certificates”

Alice’s Certificate, signed by CA

Name=Alice
Public key= 489024729

CA’s signature

Communication using certs

Alice Bob

"Alice", [Alice's key is 24789]$_{CA}$

"Bob", [Bob's key is 34975]$_{CA}$

mutual authentication, etc.

What people do think about

- Academics worry about the math
- Standards Bodies worry about the format of the certificate

What people do think about

- Academics worry about the math
- Standards Bodies worry about the format of the certificate
- Both are important, but people should also worry about the trust model
  - I will explain what that means

PKI Models

- Monopoly
- Oligarchy
- Anarchy
- Top-down, name constraints
- Bottom-up

Monopoly

- Choose one organization, for instance, “Monopolist.org”
- Assume Monopolist.org is trusted by all companies, countries, organizations
- Everything is configured to trust Monopolist.org’s public key
- All certificates must be issued by them
- Simple to understand and implement

Monopoly

Alice

Bob

Trust Monopolist.org

[This number is Bob’s key] signed by Monopolist.org

Monopoly: What's wrong with this model?

- No such thing as "universally trusted" organization
- Monopoly pricing
- More widely it's deployed, harder to change the CA key to switch to a different CA, or even to roll-over the key
- That one organization can impersonate everyone

Oligarchy of CAs

- Everything (say browsers) configured with 100 or so trusted CA public keys
- A certificate signed by any of those CAs is trusted
- Eliminates monopoly pricing

Oligarchy

Alice

Bob

Trust any of {CA1, CA2, CA3, …CAn}

[This number is Bob's key] signed by CAi

What’s wrong with oligarchy?

- Less secure!
  - Any of those organizations can impersonate anyone

Important Enhancement: Certificate Chains

- Instead of presenting a certificate signed by a CA Alice knows and trusts, Bob presents a chain of certs, starting with X1, which Alice trusts

Certificate chains

Alice

Trust X1

Bob

[X1 says α is X2's key] signed by X1's key

[X2 says β is X3's key] signed by α

[X3 says δ is Bob's key] signed by β

Certificate chains

Alice

Trust X1

Bob

[X1 says α is X2's key] signed by X1's key

[X2 says β is X3's key] signed by α

[X3 says δ is Bob's key] signed by β

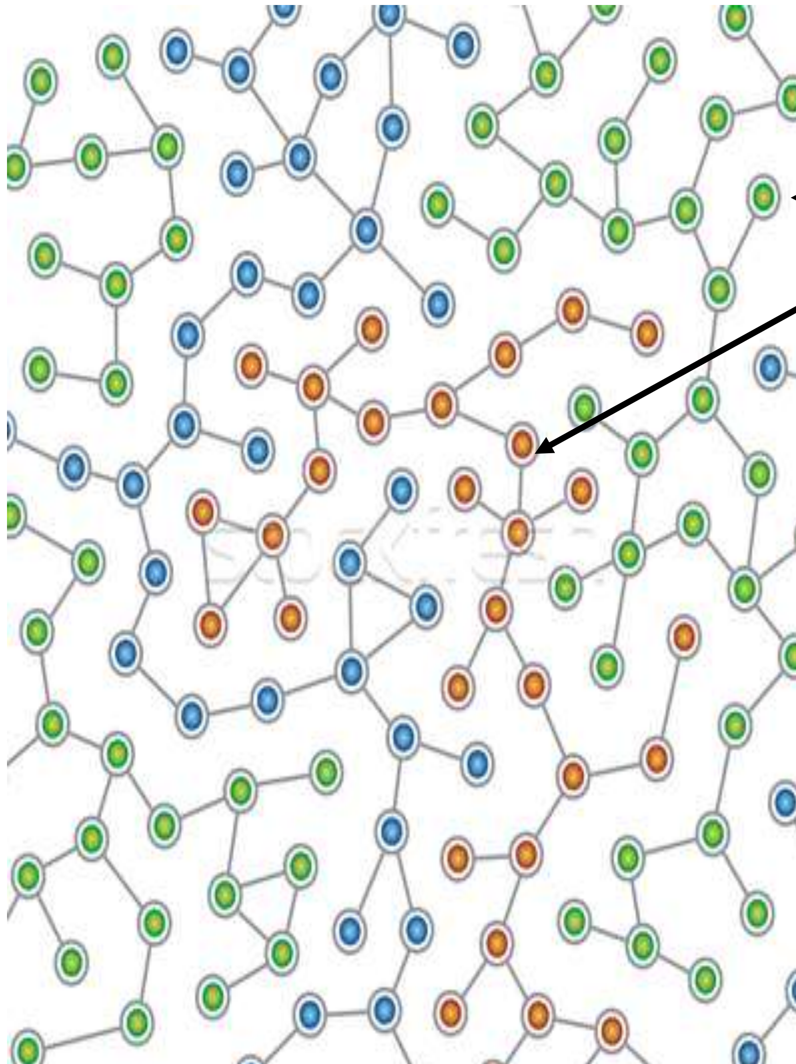
Next model: Anarchy

Anarchy

- User personally configures trust anchors
- Anyone signs certificate for anyone else
- Public databases of certs (read and write)
- Alice tries to find a path from a key her machine knows, to the target name, by piecing together a chain

Unstructured certs, public database

Alice wants Bob’s key



Alice configured with these

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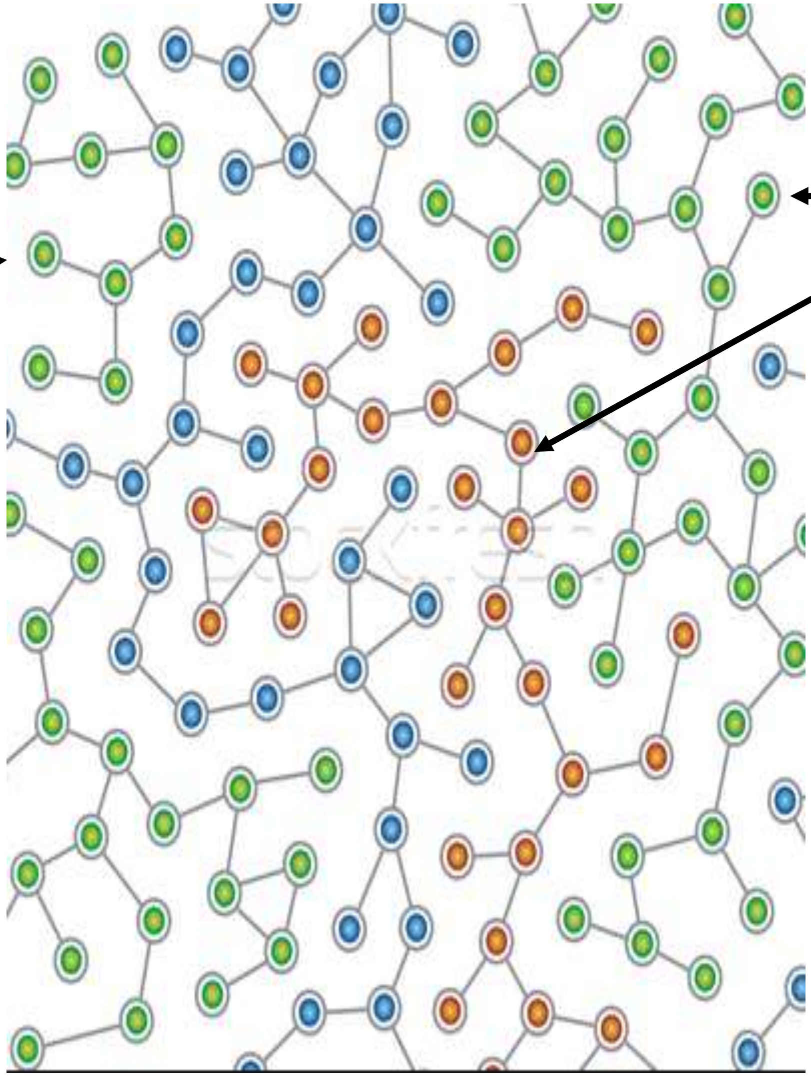

This cert says α is Bob's key

Alice configured with these

Unstructured certs, public database

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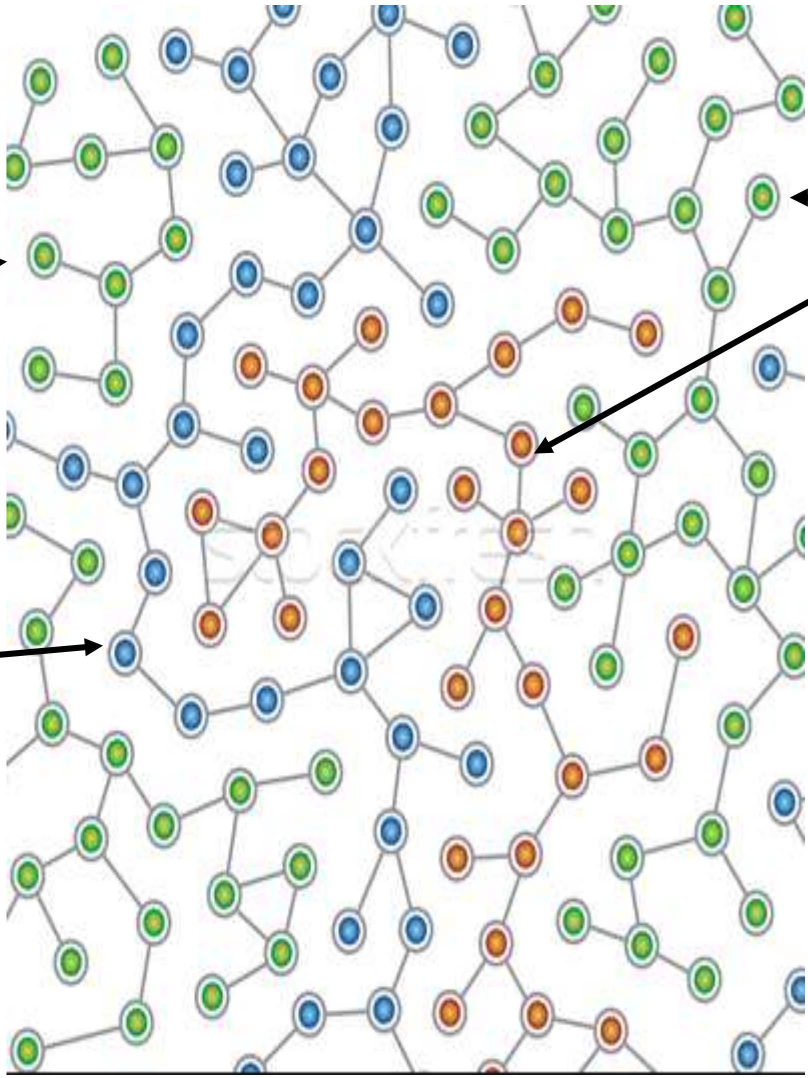
This cert says β is Bob’s key



Alice configured with these

Anarchy

- Problems
  - won’t scale (too many certs, computationally too difficult to find path)
  - no practical way to tell if path should be trusted
  - (more or less) anyone can impersonate anyone

Now I’ll talk about how I think it should work

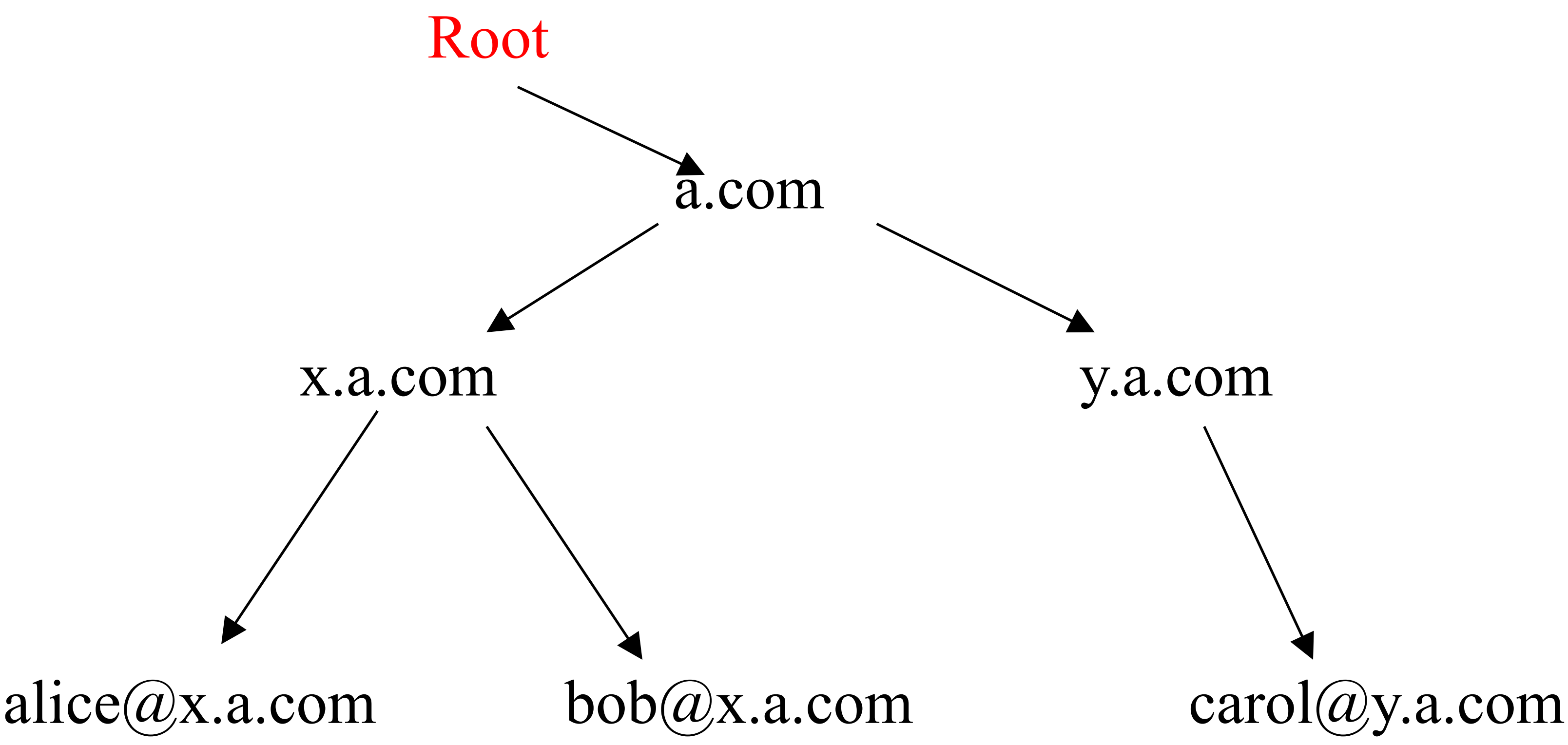
Now getting to recommended model

- Important concept:
  - CA trust isn't binary: "trusted" or "not"
- CA only trusted for a portion of the namespace
  - The name by which you know me implies who you trust to certify my key
    - Radia.perlman.emc.com
    - Roadrunner279.socialnetworksite.com
    - Creditcard#8495839.bigbank.com
  - Whether these identities are the same carbon-based life form is irrelevant

Need hierarchical name space

- Yup! We have it (DNS)
- Each node in namespace represents a CA

Top-down model (almost what we want)



Top-down model

- Everyone configured with root key
- Easy to find someone's public key (just follow namespace)

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- Everyone configured with root key
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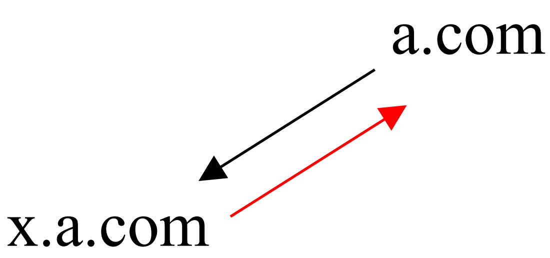
- Problems:
  - Still monopoly at root
  - Root can impersonate everyone
  - Every CA on path from Root to target can impersonate target node

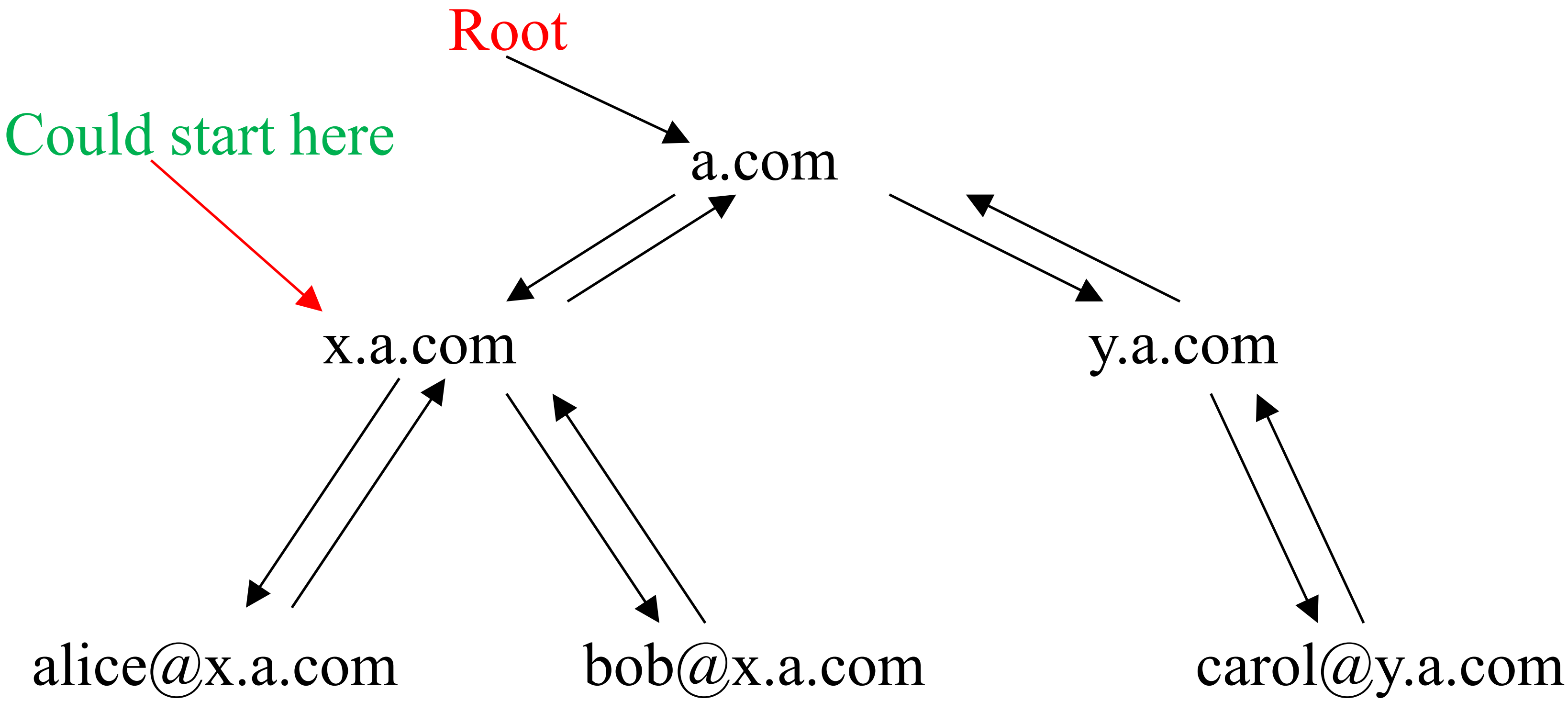
Bottom-Up Model (what I recommend)

Two-way certificates (up and down)

- Each arc in name tree has parent certificate (up) and child certificate (down)



No need to start at the Root



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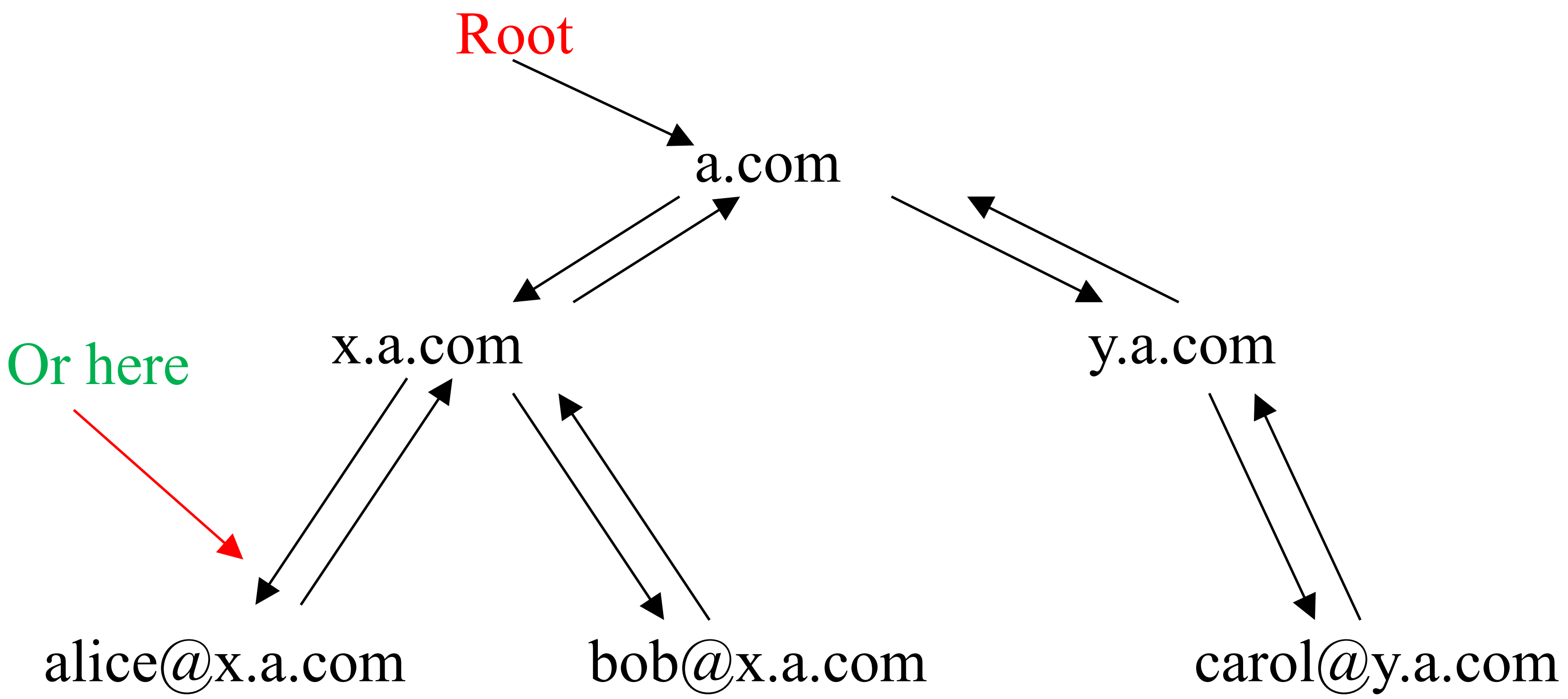

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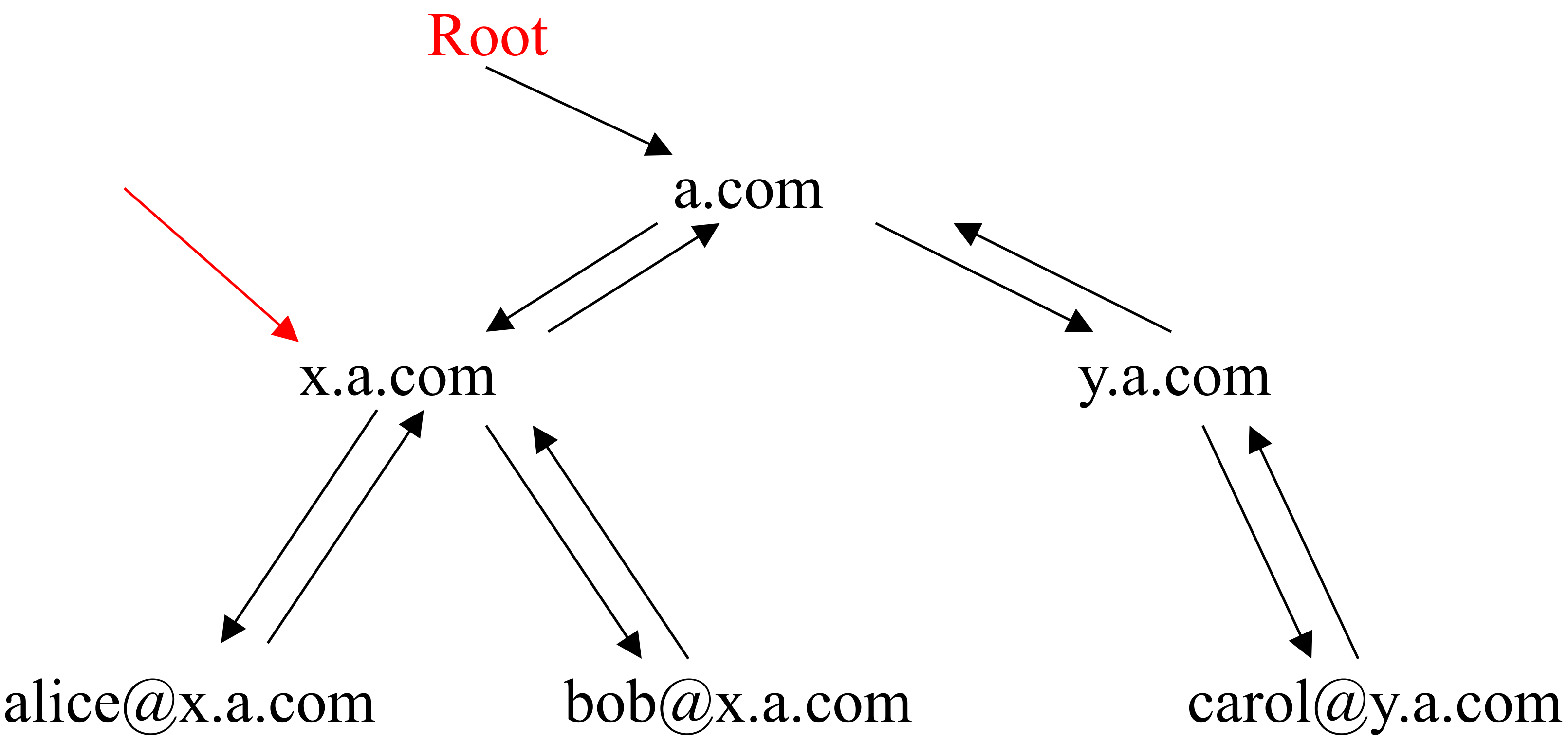
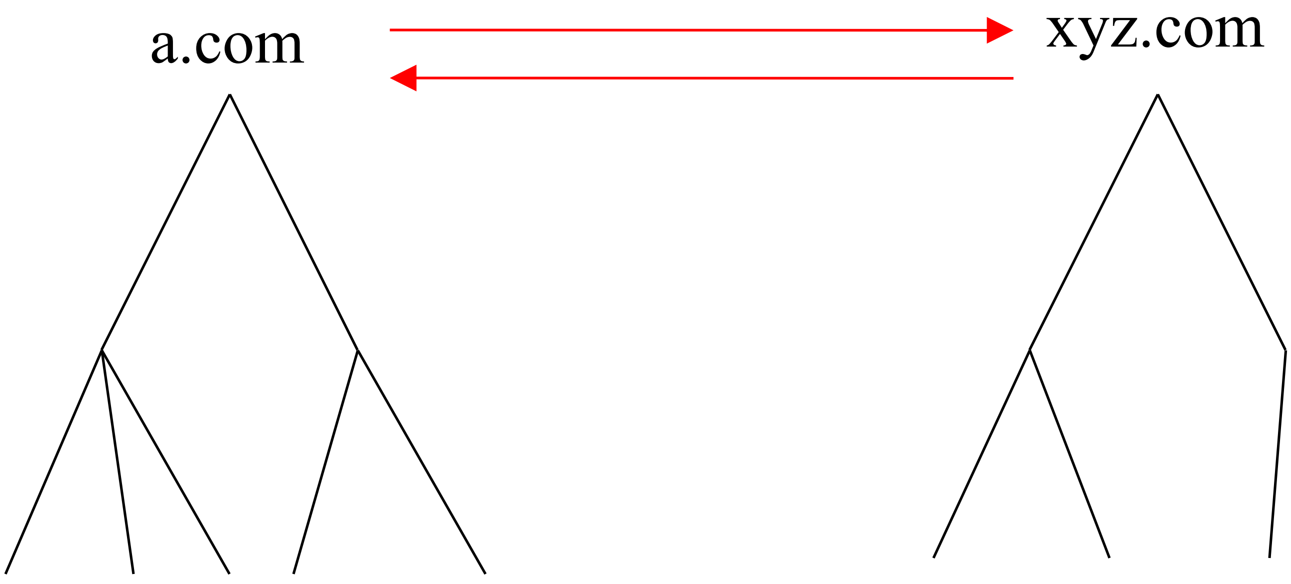


In subtree below x.a.com, fewer CAs to trust
(a.com, and Root, aren’t on path to nodes in subtree)

Another enhancement: “Cross-certificates”

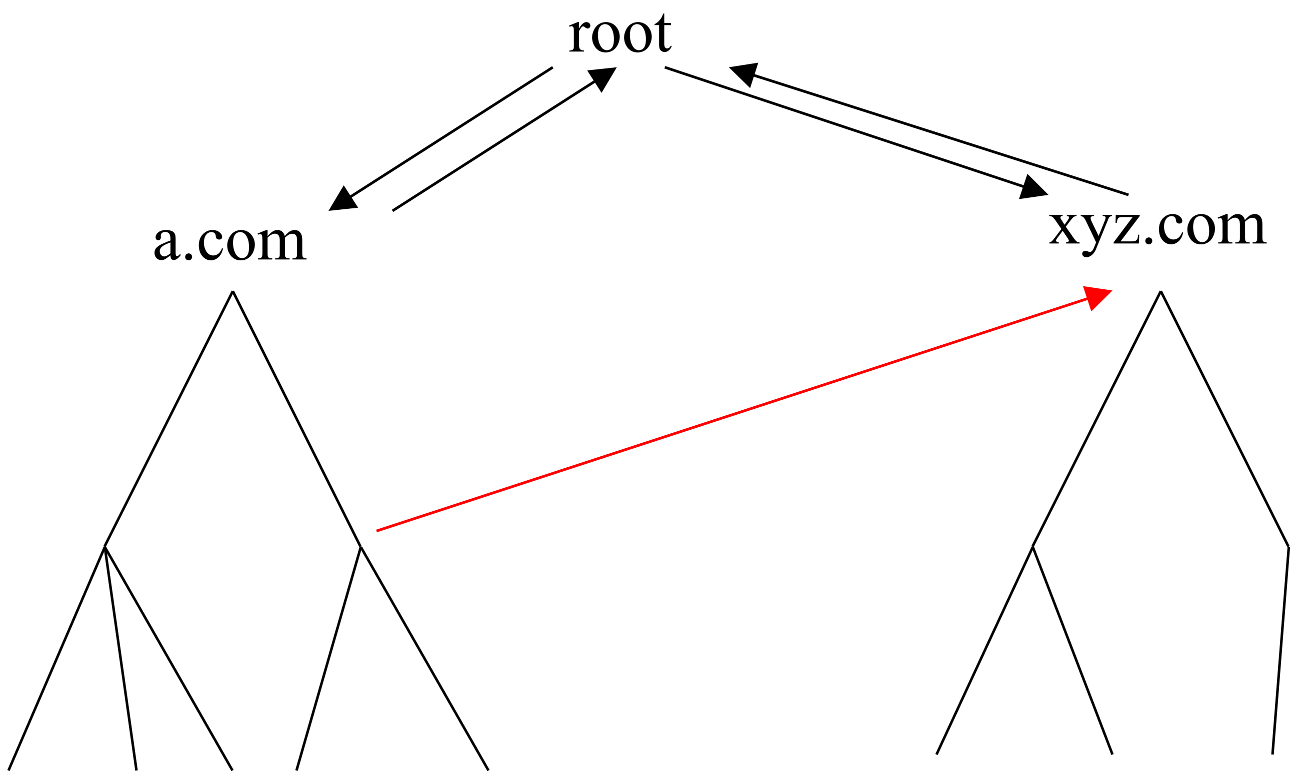
- Cross-cert: Any node can certify any other node’s key
- Two reasons:
  - So you don’t have to wait for PKI for whole world to be created first
  - Can bypass hierarchy for extra security

Cross-links to connect two organizations



Nodes in a.com and xyz.com subtrees can find each other's key.
No need for Root, or entire connected PKI

Cross-link for added security



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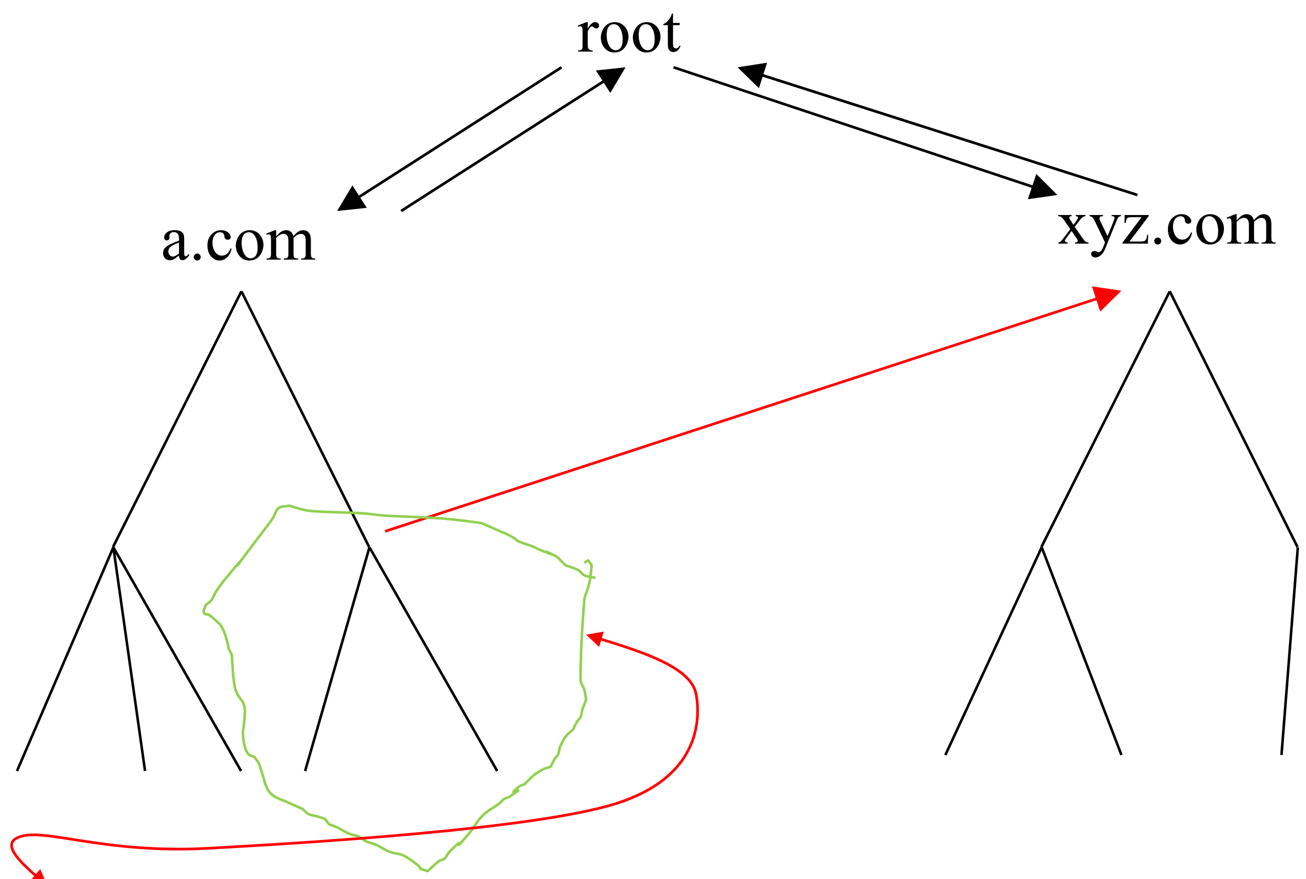


Nodes in this subtree can bypass root, and a.com

Navigation Rules

- Start somewhere (your “root of trust” .. could be your own public key)
- If you’re at an ancestor of the target node, follow down-links
- Else, look for cross-link to ancestor, and if so, follow that
- Else, go up a level

Note: Crosslinks do not create anarchy model

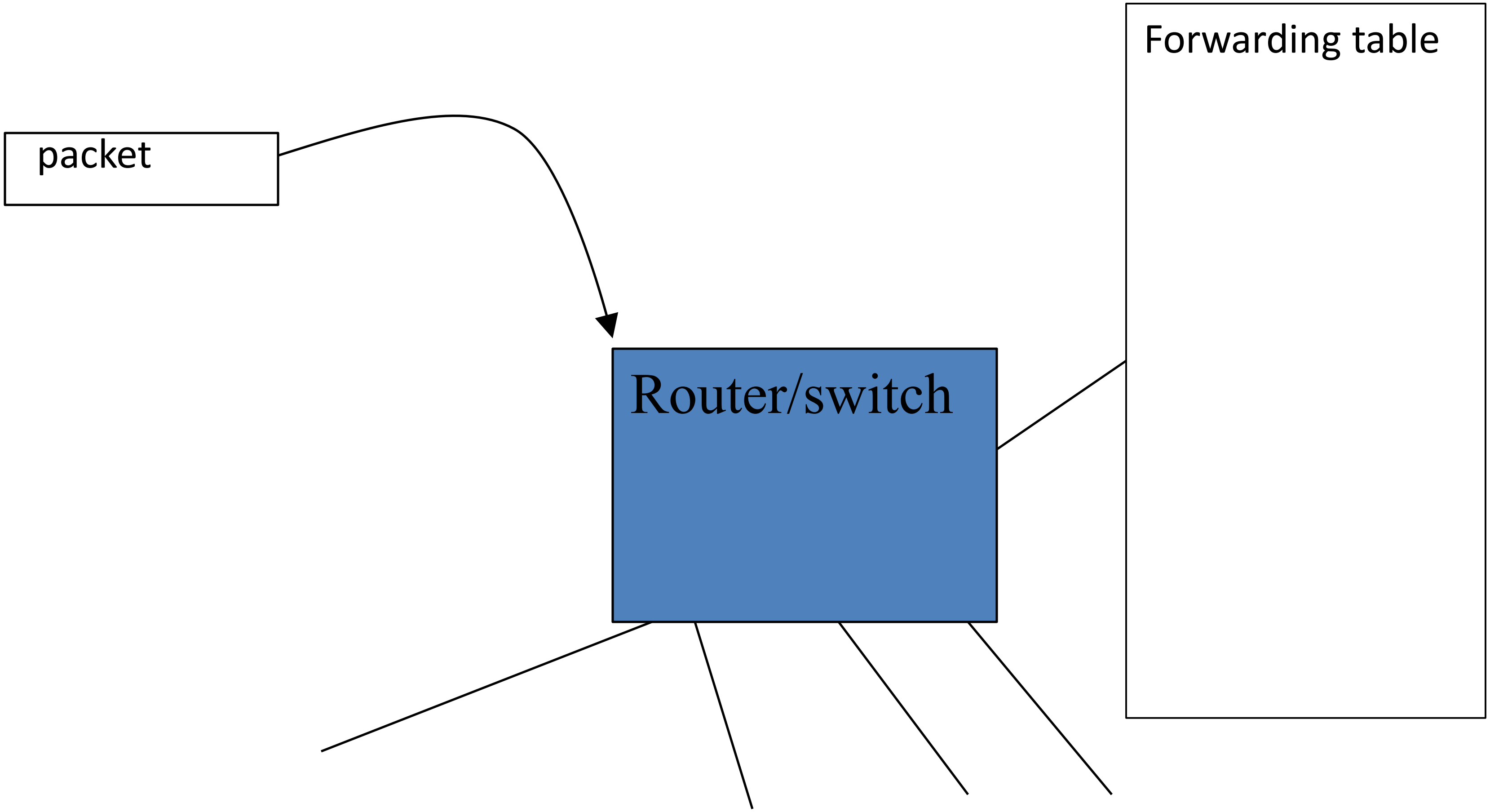
- You only follow a cross-link if it leads to an ancestor of target name

Advantages of Bottom-Up

- Security within your organization is controlled by your organization (CAs on path are all yours)
- No single compromised key requires massive reconfiguration
- Easy to compute paths; trust policy is natural, and makes sense
- Malicious CA’s can be bypassed, and damage contained

Example 2: Network Routing

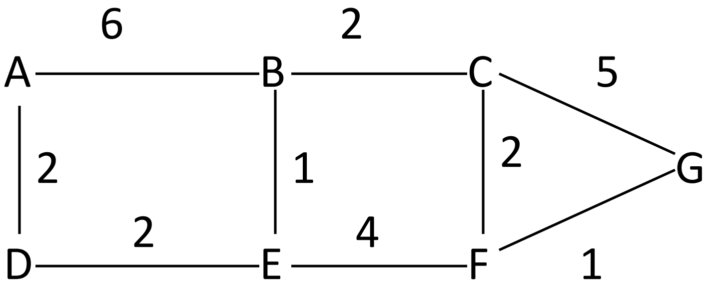
Traditional Router/switch



Computing the Forwarding Table

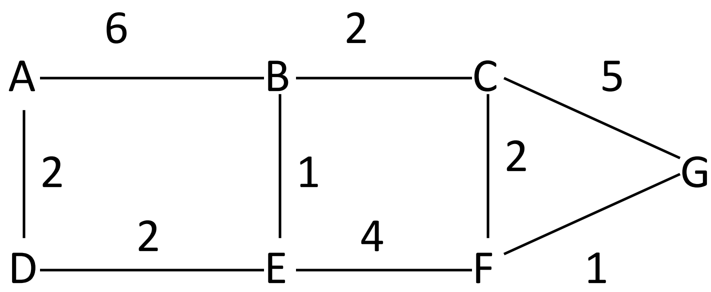
- Distributed computation of forwarding tables with link state protocol

Link State Routing



A network

Link State Routing



A	B	C	D	E	F	G
B/6	A/6	B/2	A/2	B/1	C/2	C/5
D/2	C/2	F/2	E/2	D/2	E/4	F/1
	E/1	G/5		F/4	G/1	

What about malicious switches?

- They can
  - Give false info in the routing protocol
  - Flood the network with garbage data
  - Forward in random directions, resetting the hop count on packets to look new
  - Do everything perfectly, but throw away traffic from a particular source

All sorts of traditional different approaches

- Try to agree who the bad guy(s) are
  – Reputation (problems: who do you believe, bad guys can create arbitrarily many identities, what if bad guy is only bad to one source?)
  – Troubleshooting (can be well-behaved when testing)
- Enforce routing protocol correctness
  – 2-way links
  – S-BGP
  – But that's just routing protocol. Who cares about that? You want your packets delivered.

My thesis (1988)

- Want to guarantee A and B can talk provided at least one honest path connects them
  - With reasonably fair share of bandwidth
  - “Honest path” means all switches on that path are operating properly

Flooding

- Transmit each packet to each neighbor except the one from which it was received
- Have a hop count so packets don't loop infinitely
- This works! Pkts between A and B flow, if there is at least one nonfaulty path…

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- Have a hop count so packets don't loop infinitely
- This works! Pkts between A and B flow, if there is at least one nonfaulty path…
- *If there is infinite bandwidth….whoops!*

So, just a resource allocation problem

- The finite resources are
  - computation in switches
    - assume we can engineer boxes to keep up with wire speeds
  - memory in switches
  - bandwidth on links

Byzantinely Robust Flooding

- Memory
  - reserve a buffer for each source
- Bandwidth
  - round-robin through buffers

Byzantinely Robust Flooding

- Source signs packet
  - (prevent someone occupying source's buffer)
- Put sequence number in packet
  - (prevent old packets reinjected, starving new one)

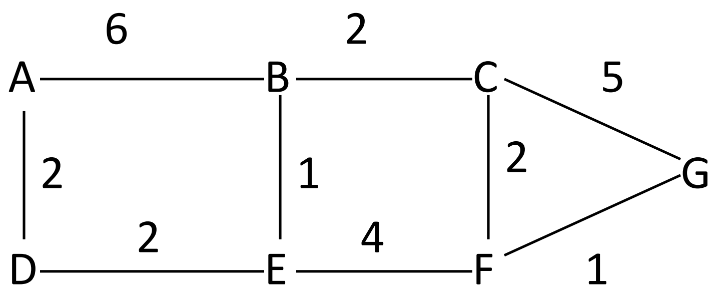
Configuration

- Every node needs other nodes' public keys; would be a lot of configuration
- So instead have "trusted node" TN (similar function to a CA)
  - TN knows all other nodes' public keys
  - All other nodes need their own private key, and the trusted node public key
- Since everyone knows TN's public key, TN can flood
  - Info it floods: all nodes' public keys

Inefficient to send data with flooding

- So, we'll do something else for unicast
- But we will use robust flooding for two things
  - easing configuration (advertising public keys)
  - distributing link state information

Link State Routing



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Data Packets/unicast

- "Traditional" per-destination forwarding won't work
  - Bad guy can keep network in flux by flipping state of a link
  - What do you do if path works for everyone but S?

Data Packets/unicast

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  - Bad guy can keep network in flux by flipping state of a link
  - What do you do if path works for everyone but S?
- Conclusion: Source has to choose its own path

Data packets

- Source chooses a path
- Sets it up with a cryptographically signed setup packet, specifying the path
- Routers along the path have to keep per (S,D) pair
  - Input port
  - Output port
  - Buffers for data packet fwd'ed on this flow

Unicast Forwarding

- No crypto needed
- Just additional check "is it coming from expected port?"
- As long as path is honest, no malicious switch off the path can disrupt flow

Simple heuristics for S choosing a path that works for S

- If path to D works (end-to-end acks), then have more trust in routers along that path
- If path doesn't work, be suspicious of the routers on that path
- Try to eliminate routers one at a time, but if lots of bad guys, can be really expensive

Note this isn't too scalable

- Since every path requires state
- And requires source seeing entire path (which it can't in hierarchical network)
- More recent work fixes that
  - Perlman, R., Kaufman, C., "Byzantine Robustness, Hierarchy, and Scalability", IEEE Conference on Communications and Network Security, CNS 2013.

Resilience

- Source has fate in its own hands: no need for “agreement”
- Malicious TN: have multiple and vote, or just reserve resources for any public key advertised (and malicious TN can’t use up more than ½ the resources, and will be quickly caught)

Example 3: Data: Making it be there when you want it, and making it go away when you want it gone

Resilient expiring data

- Paper "File System Design with Assured Delete"
  - https://www.isoc.org/isoc/conferences/ndss/07/papers/file_system_assured_delete.pdf

Expiration time

- When create data, put (optional) "expiration date" in metadata
- After expiration, data must be unrecoverable, even though backups will still exist

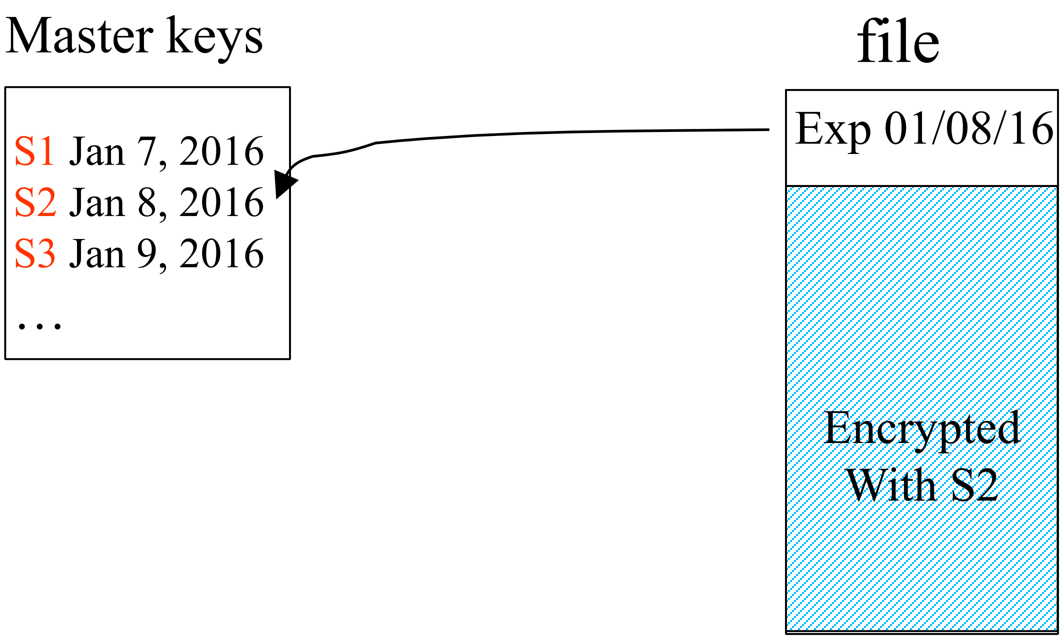
Obvious approach

- Encrypt the data, and then destroy keys
- But to avoid prematurely losing data, you'd have to make lots of copies of the keys
- Which means it will be difficult to ensure all copies of backups of expired keys are destroyed

First concept: Encrypt all files with same expiration date with the same key

File system with Master keys

Master keys: Secret keys (e.g., AES)
generated by storage system
Delete key upon expiration



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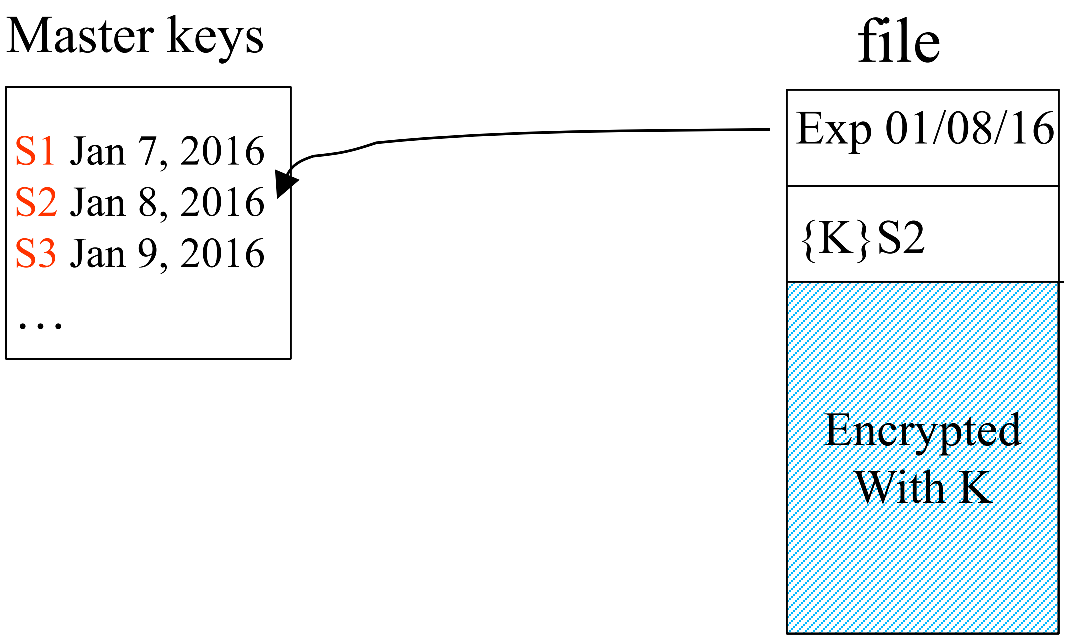


How many keys?

- If granularity of one per day, and 30 years maximum expiration, 10,000 keys

So…how do you back up the master keys?

Imagine a service: An "ephemerizer"

- creates, advertises, protects, and deletes public keys
- Storage system "ephemerizes" each master key on backup, by encrypting with (same expiration date) ephemerizer public key
- To recover from backup: storage system asks ephemerizer to decrypt

Ephemerizer publicly posts

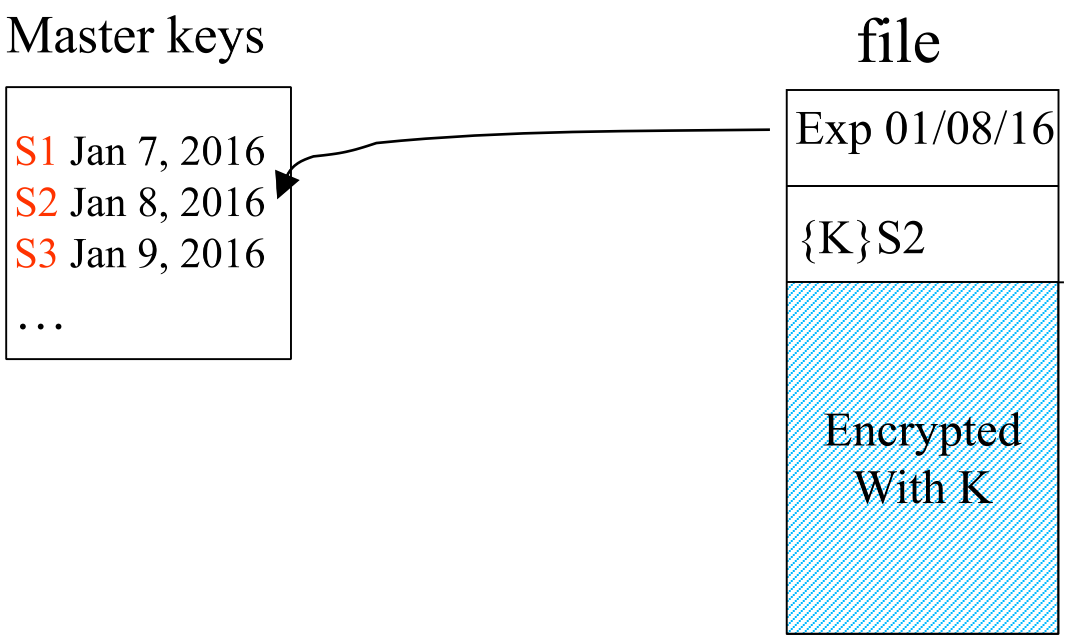
Jan 7, 2016: public key $P_{Jan7of2016}$
Jan 8, 2016: public key $P_{Jan8of2016}$
Jan 9, 2016: public key $P_{Jan9of2016}$
Jan 10, 2016: public key $P_{Jan10of2016}$

etc

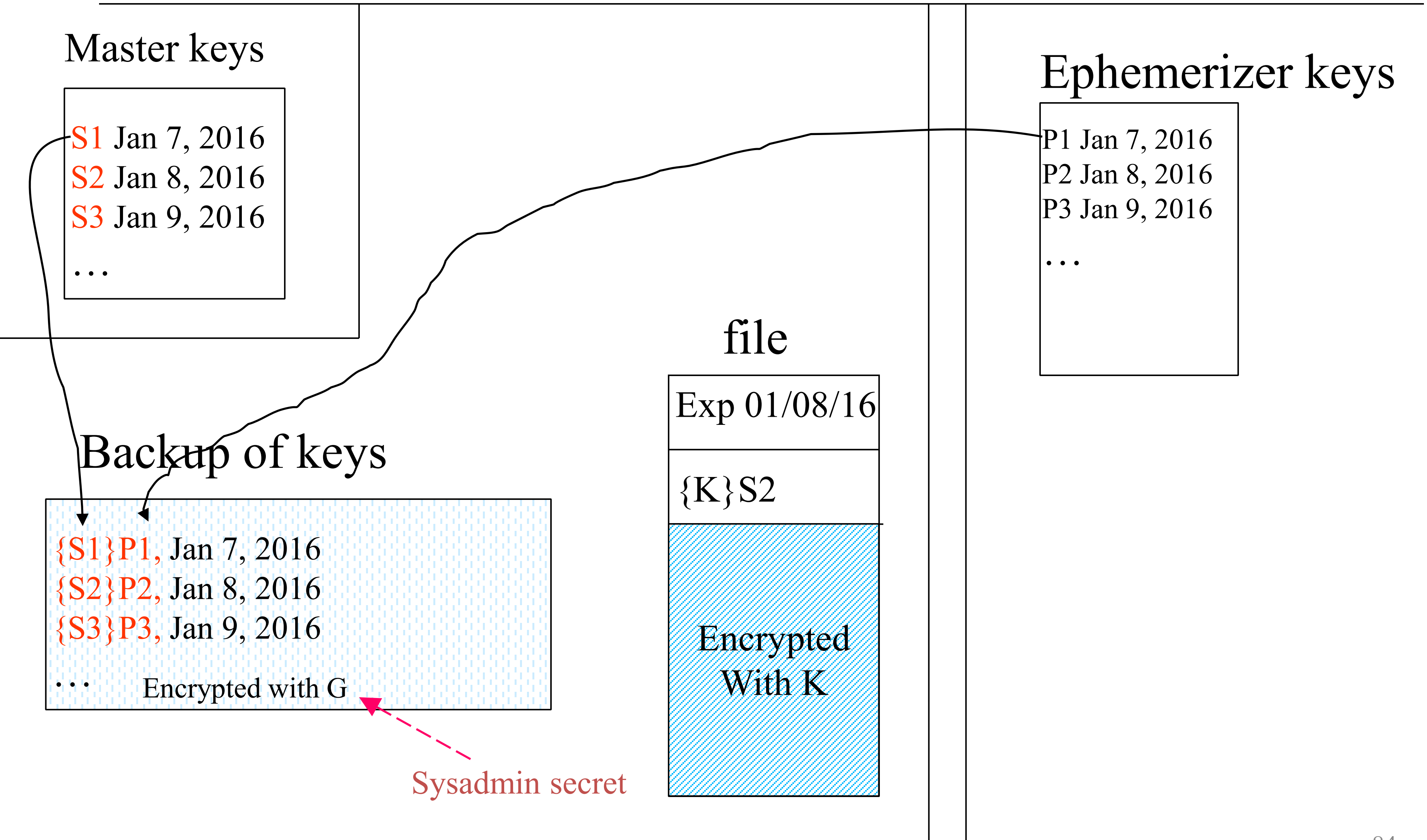
One permanent public key P certified through PKI
Signs the ephemeral keys with P

Storage system with Master keys

Master keys: Secret keys (e.g., AES) generated by storage system



Backup of Master Keys



Notes

- Only talk to the ephemerizer if your hardware with master keys dies, and you need to retrieve master keys from backup
- Ephemerizer really scalable:
  – Same public keys for all customers (10,000 keys for 30 years, one per day)
  – Only talk to a customer perhaps every few years…to unwrap keys being recovered from backup

But you might be a bit annoyed at this point

But you might be a bit annoyed at this point

- Haven’t we simply pushed the problem onto the ephemerizer?
- It has to reliably keep private keys until expiration, and then reliably delete them

Two ways ephemerizer can “fail”

- Prematurely lose private keys
- Fail to forget private keys

Two ways ephemerizer can "fail"

- Prematurely lose private keys
- Fail to forget private keys
- Let's worry about these one at a time…first worry about losing keys prematurely

Losing keys prematurely

- We will allow an ephemerizer to be flaky, and lose keys
- Generate keys, and do decryption, on tamper-proof module
- An honest ephemerizer should not make copies of its ephemeral private keys
- So…wouldn't it be a disaster if it lost its keys when a customer needs to recover from backup?

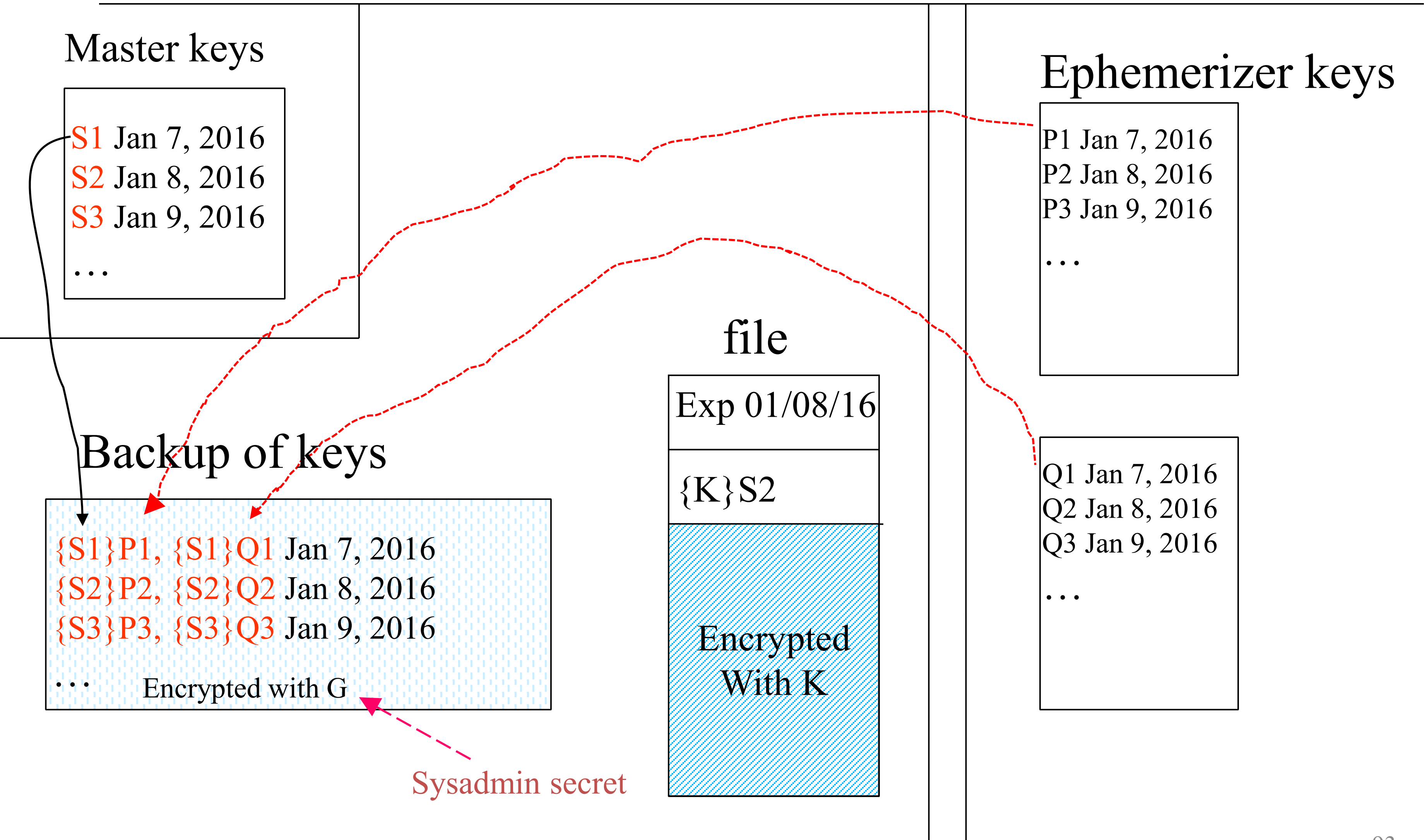
Question: How many copies of private keys should ephemerizer keep so you feel safe?

- Let’s say 20

The reason why it's not just pushing the problem

- You can achieve arbitrary robustness by using enough "flaky" ephemerizers!
  - Independent ephemerizers
    - Different organizations
    - Different countries
    - Different continents
  - Independent public keys

Use multiple ephemerizers!



What if ephemerizer doesn't destroy private key when it should?

- Then the storage system can use a quorum scheme (k out of n ephemerizers)
  - Break master key into n pieces, such that a quorum of k can recover it
  - Encrypt each piece with each of the n ephemerizers' public keys

So, after disaster, 10,000 decryptions

- Not so bad, but we can do better

No reason keys have to be independent random numbers

- We could make day n+1 key one-way hash of day n key (or store it encrypted with day n's key)
- Then we only need to ask for a single decryption after a disaster (the one closest to expiration)
- And we can locally derive the rest of the keys

Ephemerizer decryption protocol

- Protocol for asking ephemerizer to decrypt
  - That doesn’t let the ephemerizer see what it’s decrypting
  - Doesn’t require authentication of either end
  - Super light-weight (can be one IP packet each direction, very little computation)

I’ll skip over how

- Because I’m sure we’ll be short on time
- But I’m leaving the slides there

What we want to accomplish

File system

Ephemerizer

Has $\{S_i\}P_i$

Please decrypt $\{S_i\}P_i$ with key ID i $\rightarrow$

use private key i

$\leftarrow S_i$

What we want to accomplish

File system

Ephemerizer

Has $\{S_i\}P_i$

Please decrypt $\{S_i\}P_i$ with key ID i $\longrightarrow$

use private key i

$\longleftarrow S_i$

But we don't want the Ephemerizer to see S_i

We’ll use “blind decryption”

- FS wants Eph to decrypt {Si}Pi with Eph’s private key #i
  - … Without Eph seeing what it is decrypting
- FS chooses inverse functions
  - “blind/unblind” (B, U)
- encrypts (blinds) with Blind Function, which commutes with Eph’s crypto
- Then FS applies U to unblind

Using Blind Decryption

File system

Ephemerizer

Has $\{S_i\}P_i$

Invents functions (B,U) just for this conversation

Please decrypt **B**$\{\{S_i\}P_i\}$ with key ID i

use private key i

B$\{S_i\}$

File system applies U to get S_i

Ephemerizer only sees B$\{S_i\}$

Non-math fans can take a nap

For you math fans…

Quick review of RSA

- Public key is (e,n). Private key is (d,n), where e and d are "exponentiative inverses mod n"
- That means X^{ed} mod n=X
- Encrypt X with public key (e,n) means computing X^e mod n

Blind Decryption with RSA, Eph's RSA PK=(e,n), msg=M

File System

Ephemerizer

wants to decrypt M^e mod n

chooses R, computes R^e mod n

$M^e \ R^e$ mod n $\longrightarrow$

applies (d,n)

$M^{ed}R^{ed}$

$\longleftarrow$ M R mod n

divides by R mod n to get plaintext M

Properties of our protocol

- Ephemerizer gains no knowledge when it is asked to do a decryption
- Protocol is really efficient: one IP packet request, one IP packet response
- No need to authenticate either side
- Decryption can even be done anonymously

OK, non-math fans can wake up now

Because of blind decryption

- The customer does not need to run its own Ephemerizers, or really trust the Ephemerizers very much
- Ephemeral key management can be outsourced

General philosophy

- Achieve robustness by lots of can-be-flaky components
- Failures are truly independent
  - Different organizations
  - Different administrators
  - Independent clocks

In contrast, a non-resilient solution

People kept wanting “on-demand” delete

- And I kept arguing that it was not useful, and wouldn’t be scalable

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People kept wanting “on-demand” delete

- And I kept arguing that it was not useful, and wouldn’t be scalable
- But then I realized how to do it
- And think it’s a really bad idea
- And it’s useful to see both how to do it, and why it’s a bad idea

On-demand delete

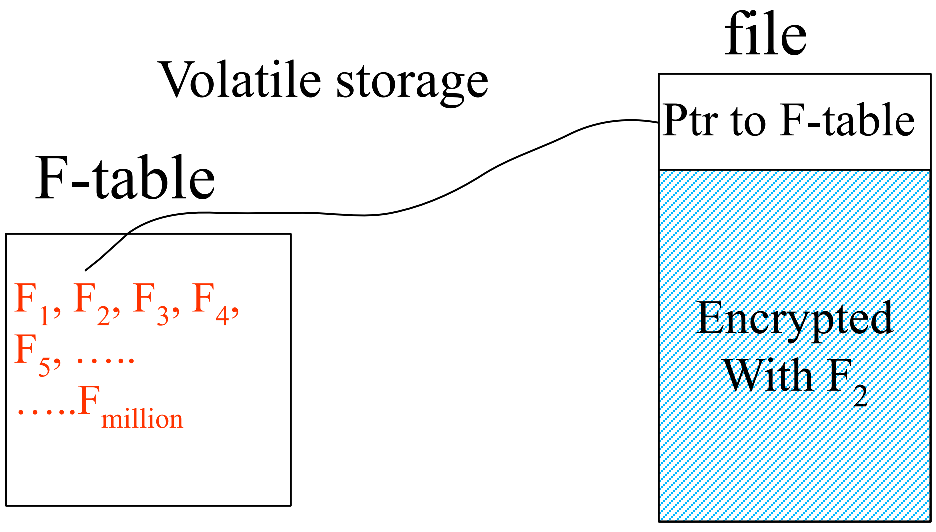
Instead of master keys

- Storage system keeps “F-table”, consisting of a secret key for each (expirable) piece of data
- Adds key to F-table when new (expirable) data stored
- Deletes key from F-table when (expirable) data is assuredly-deleted

Ephemerizer state

- In time-based system, ephemerizer didn't need to know its customers
- For the on-demand system, ephemerizer needs to keep two public keys for each customer file system
  - current public key (P_n)
  - previous public key (P_{n-1})

File system with F-table



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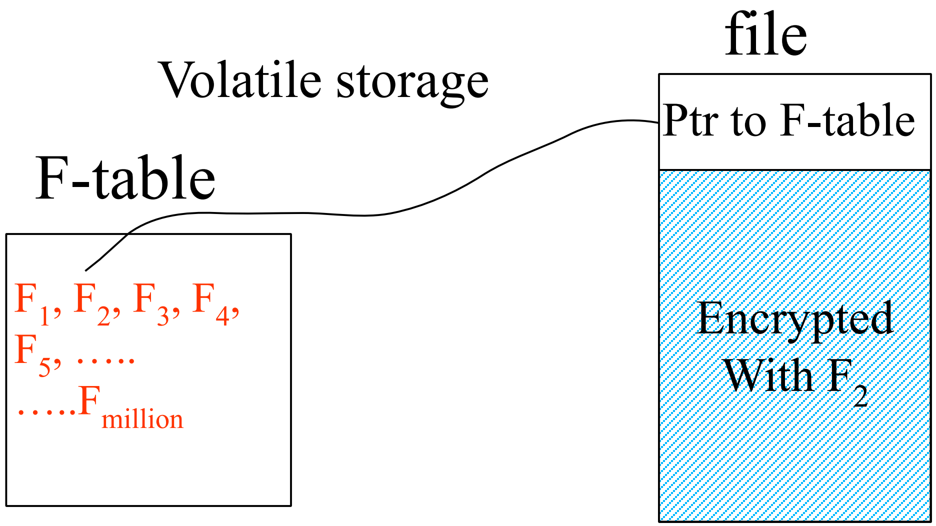
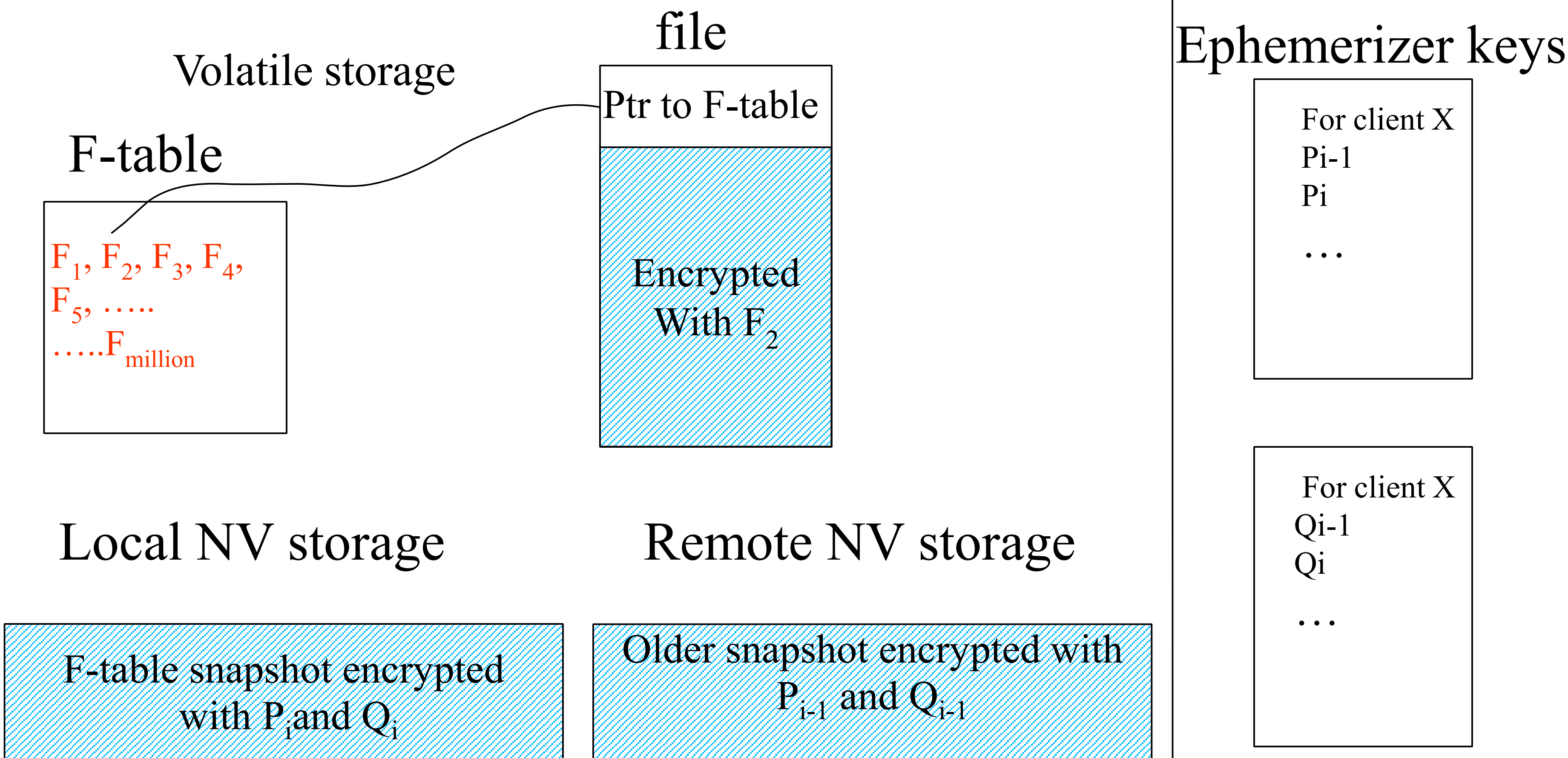


Modify F-table when you assure-delete a file
Or create a new file
F-table has key for each file…if a million files, a million keys

File system with F-table



Sufficiently replicated for robustness

So what’s wrong?

My concern

- Suppose you change P’s every week
- Suppose you find out that the file system was corrupted a month ago
- And that parts of the F-key database were corrupted, without your knowledge
- You can’t go back

Why isn't pre-determined expiration time as scary?

- If file system is not corrupted when a file is created, and the file is backed up, and the S-table is backed up, you can recover an unexpired file from backup
- Whereas with the on-demand scheme, if the file system gets corrupted, all data can get lost

Note

- I’ve shown 3 very different problems, with very different solutions
- I’m not sure there is any one piece of advice other than “think about the case of misbehaving participants”

Thank you!