Securing Untrustworthy Software Using Information Flow Control

Nickolai Zeldovich

Joint work with Silas Boyd-Wickizer, Eddie Kohler, David Mazières

Problem: Bad Code

- PayMaxx divulges social security numbers
  - Sequential account number stored in the URL
  - First account had SSN 000-00-0000, no password

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  - First account had SSN 000-00-0000, no password
- CardSystems loses 40,000,000 CC numbers
- Secret service email stolen from T-mobile
- 10,000 students data compromised at Stanford
- Don't these people know what they're doing?

Problem: Bad Code

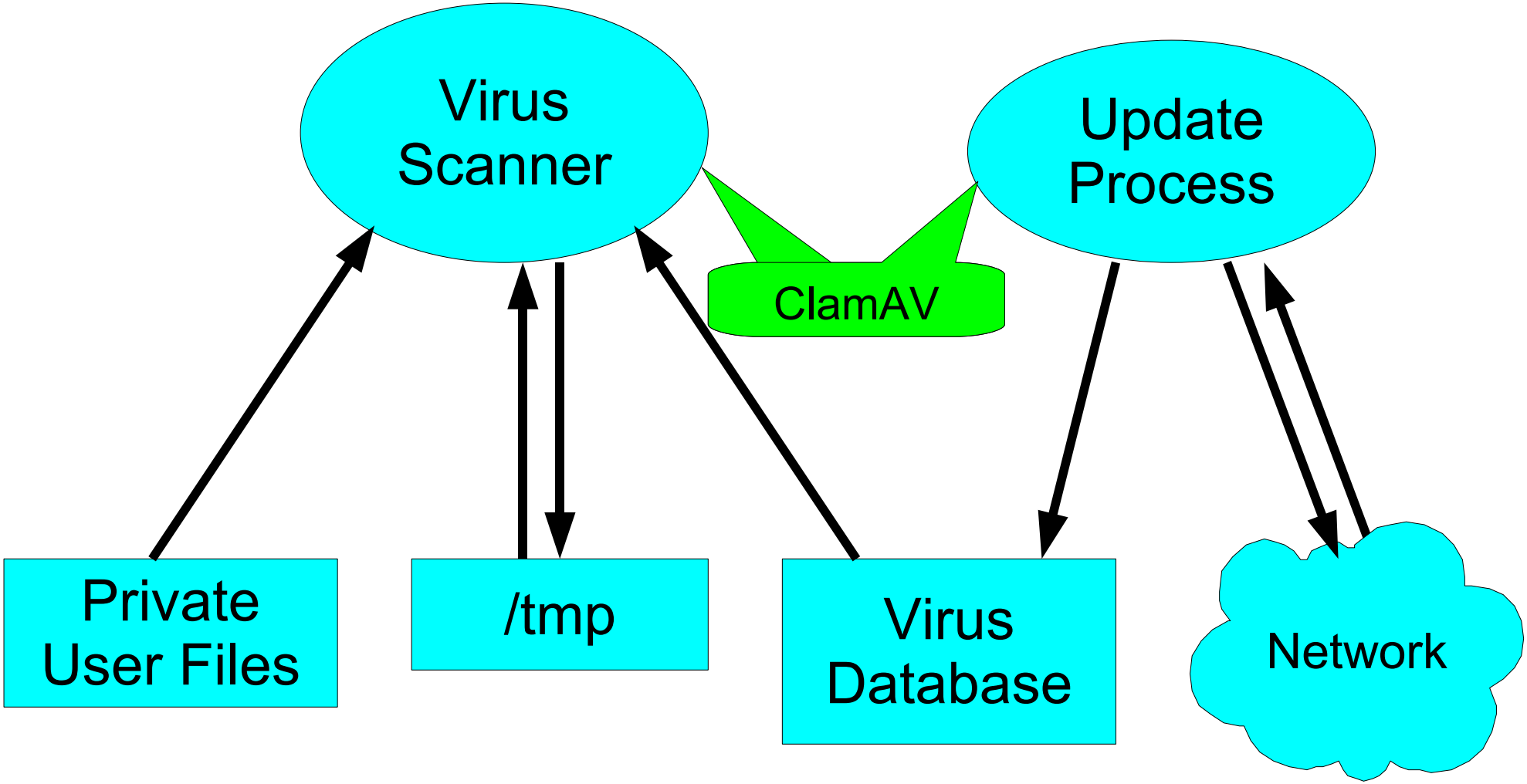
- Even *security experts* can't get it right
- May 2006: Symantec AV 10.x remote exploit
  - Software deployed on 200,000,000 machines
  - Without this software, machines also vulnerable
  - You just can't win
- If *Symantec* can't get it right, what hope is there?

Solution: Give up

- Accept that software is largely untrustworthy
- Legitimate software is often vulnerable
- Users willingly run malicious software
  - Malware, spyware, ...
- No sign that this problem is going away
- Reduce the amount of trusted software
  - Focus on **security of data**, not security of code

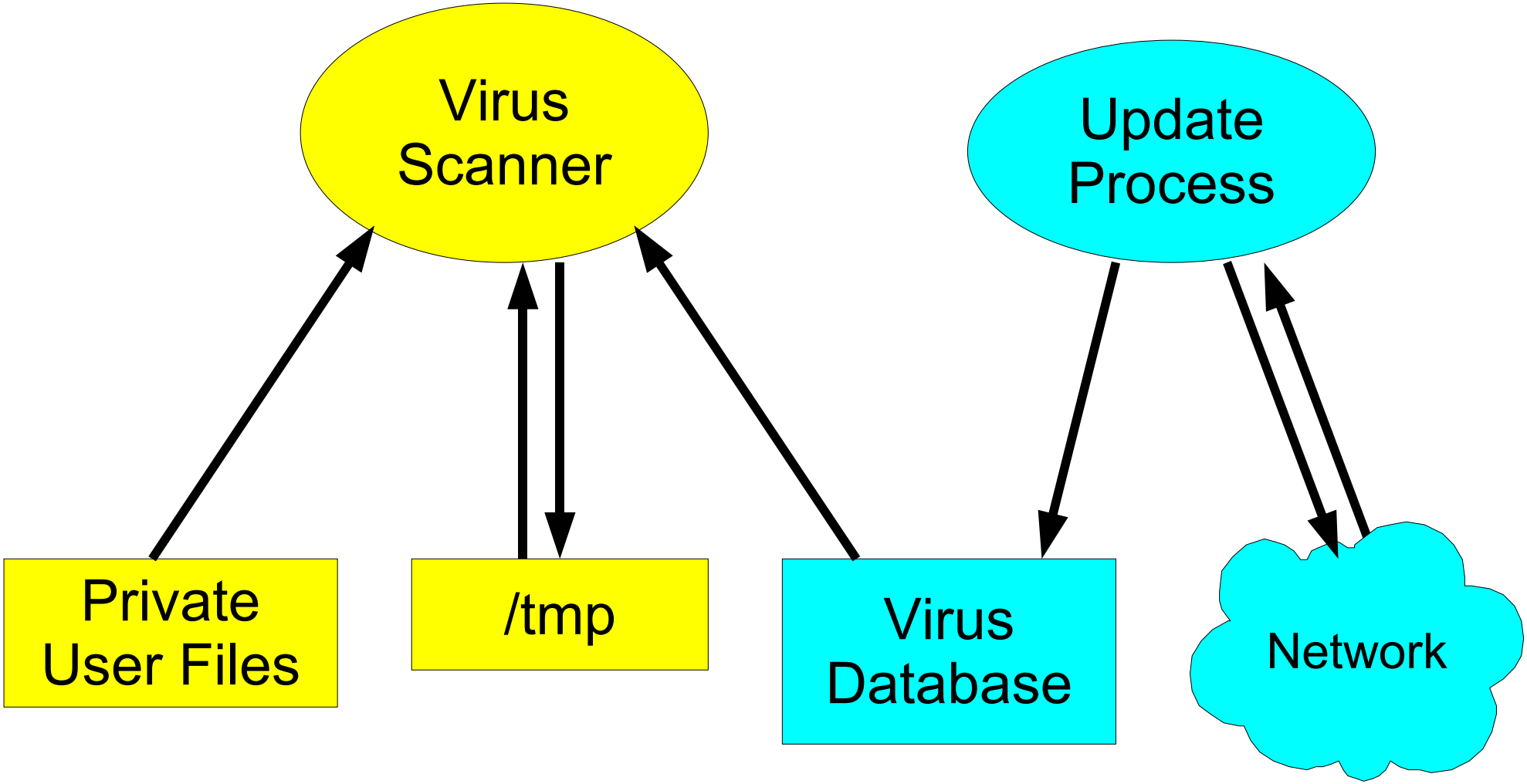
Example: Virus Scanner

- Can we eliminate trust in ClamAV?



- Goal: private files cannot go onto the network

Information Flow Control



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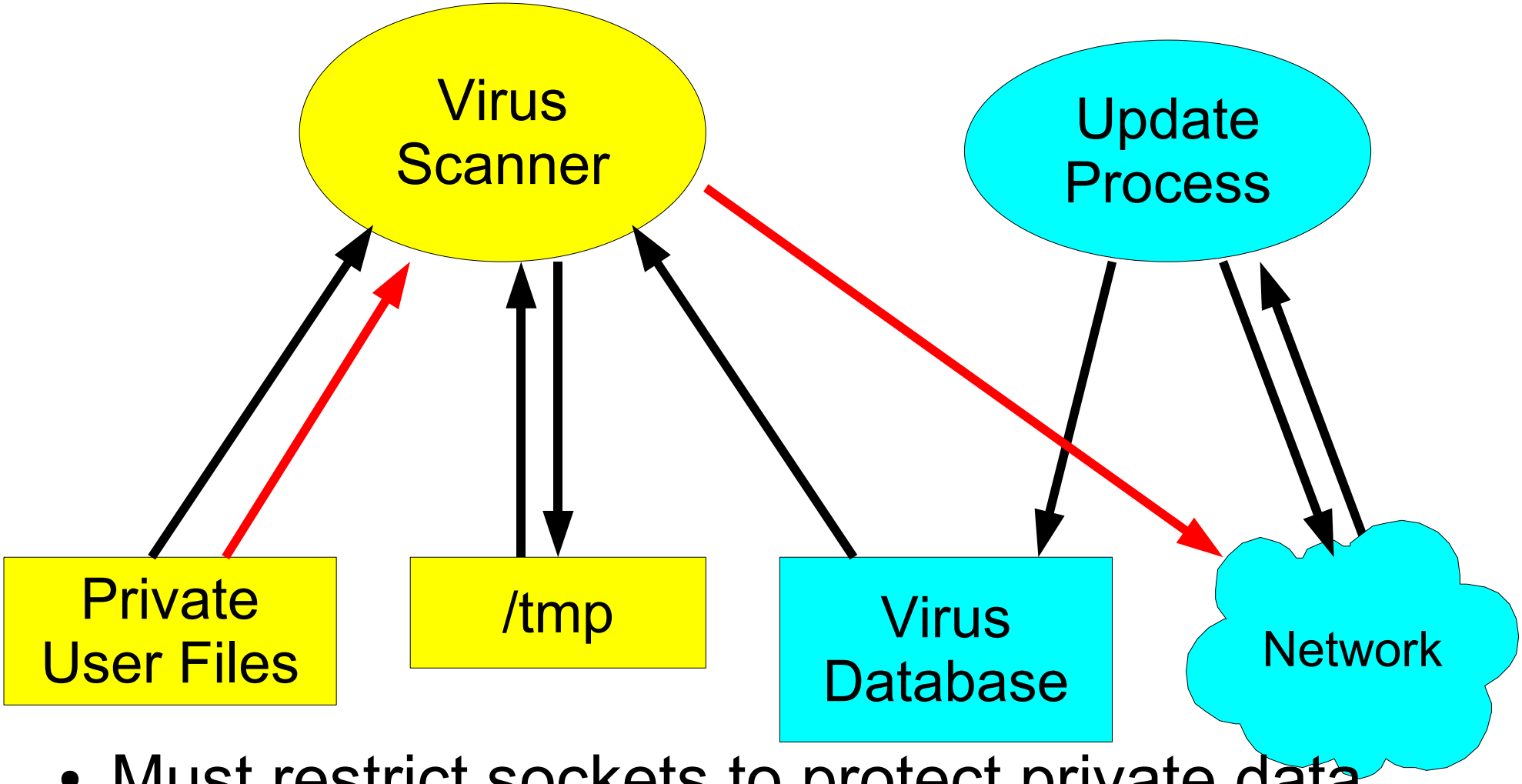
Buggy scanner leaks private data



- Must restrict sockets to protect private data

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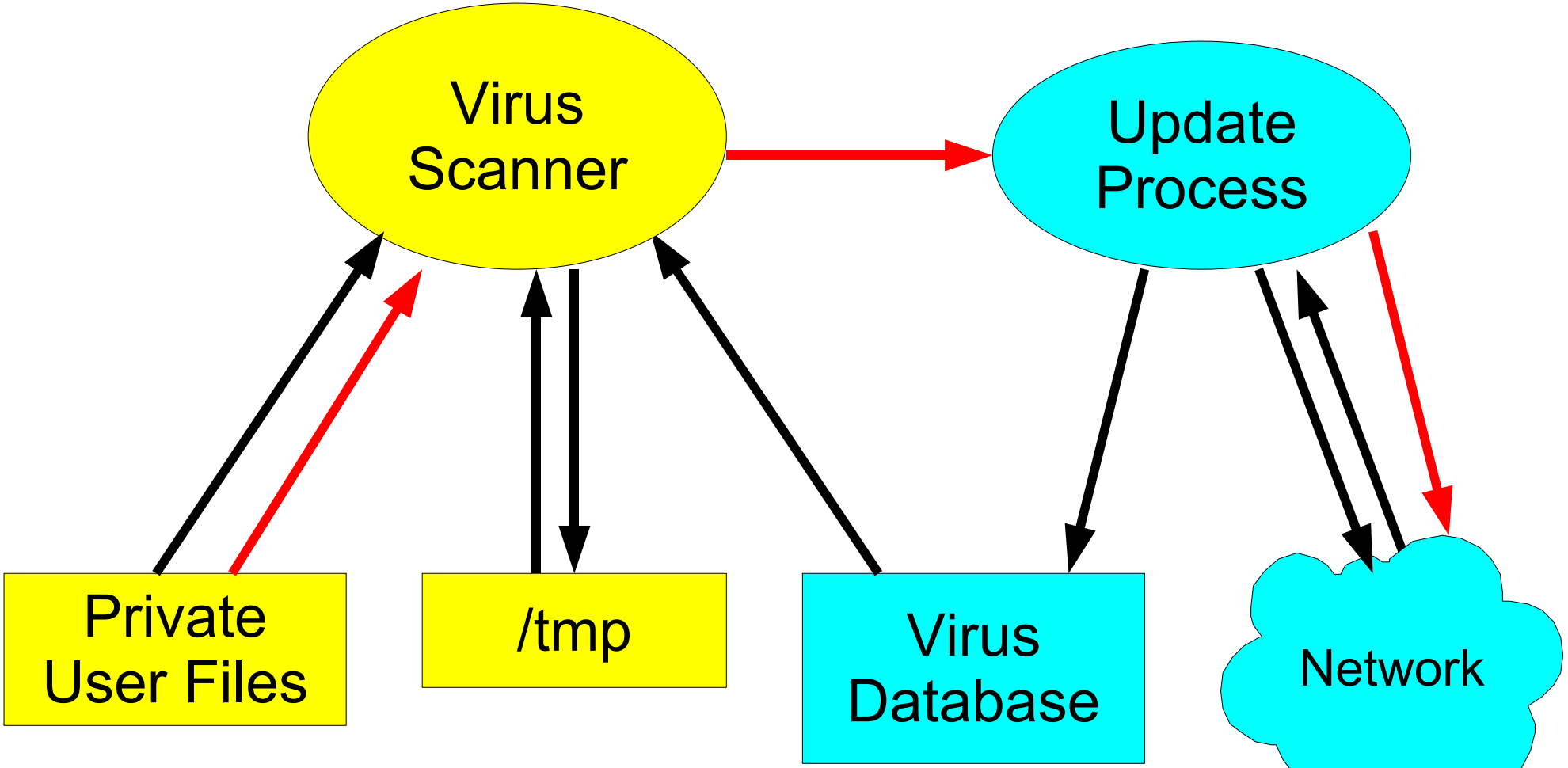
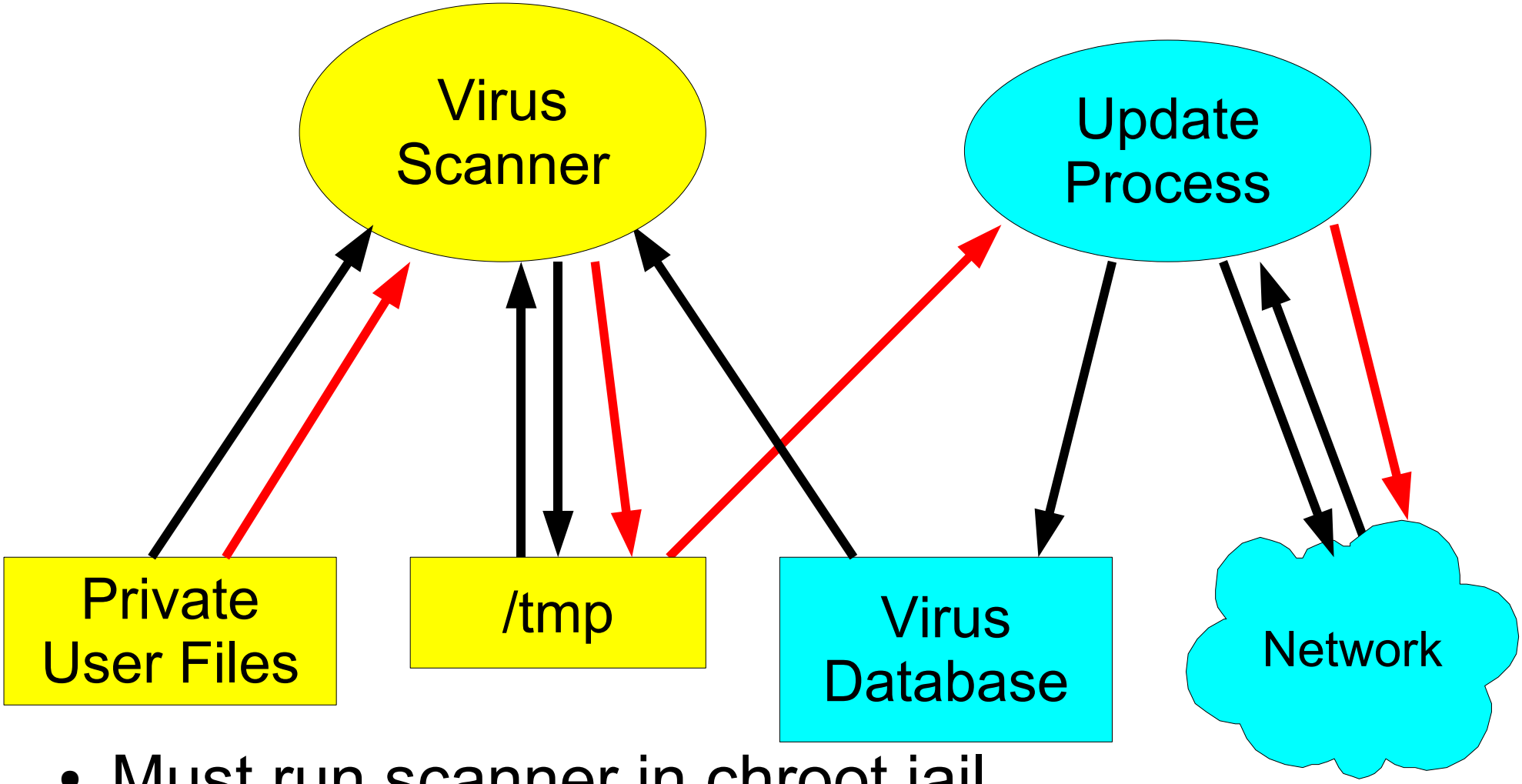


- Must restrict scanner's ability to use IPC

Buggy scanner leaks private data



- Must run scanner in chroot jail

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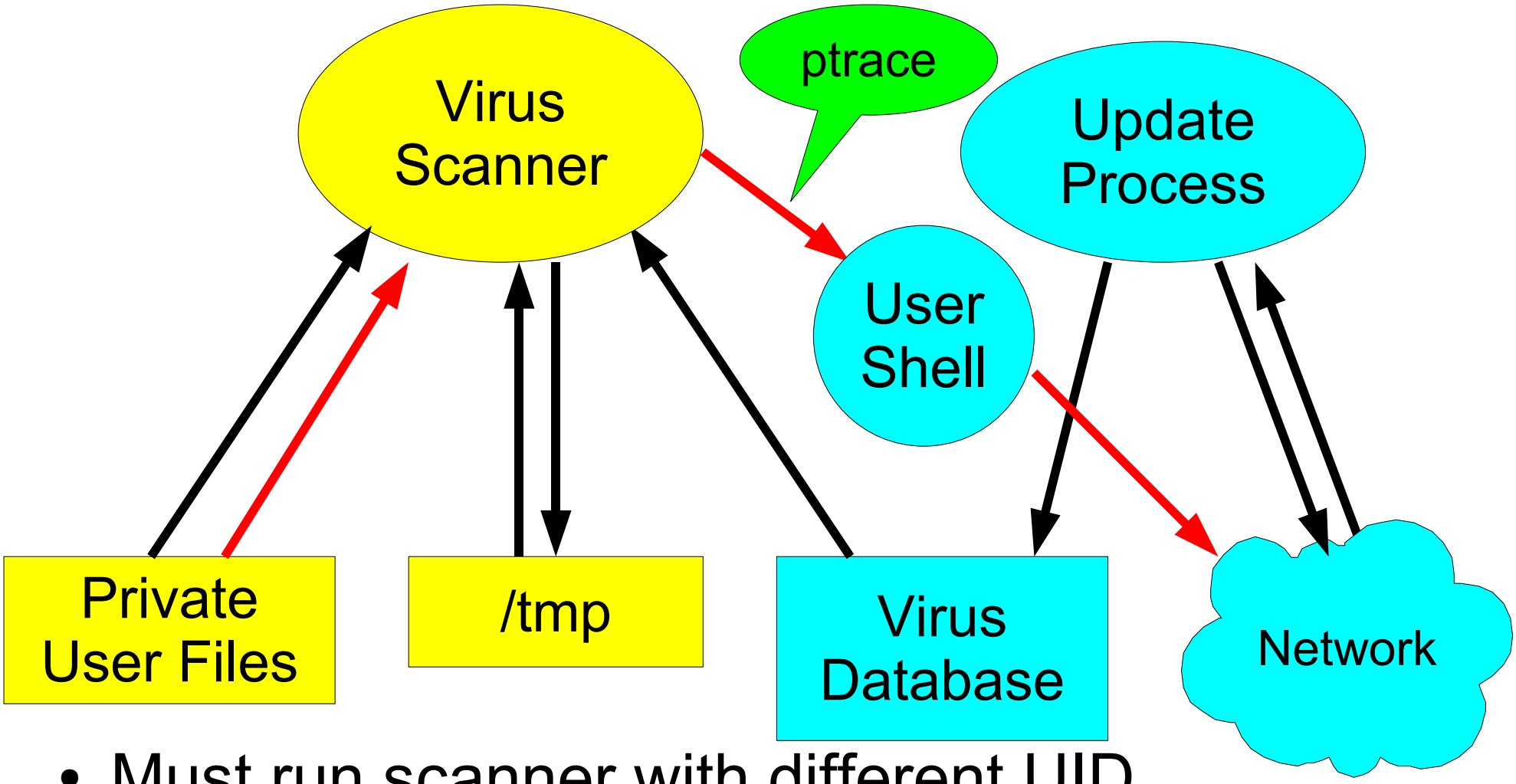
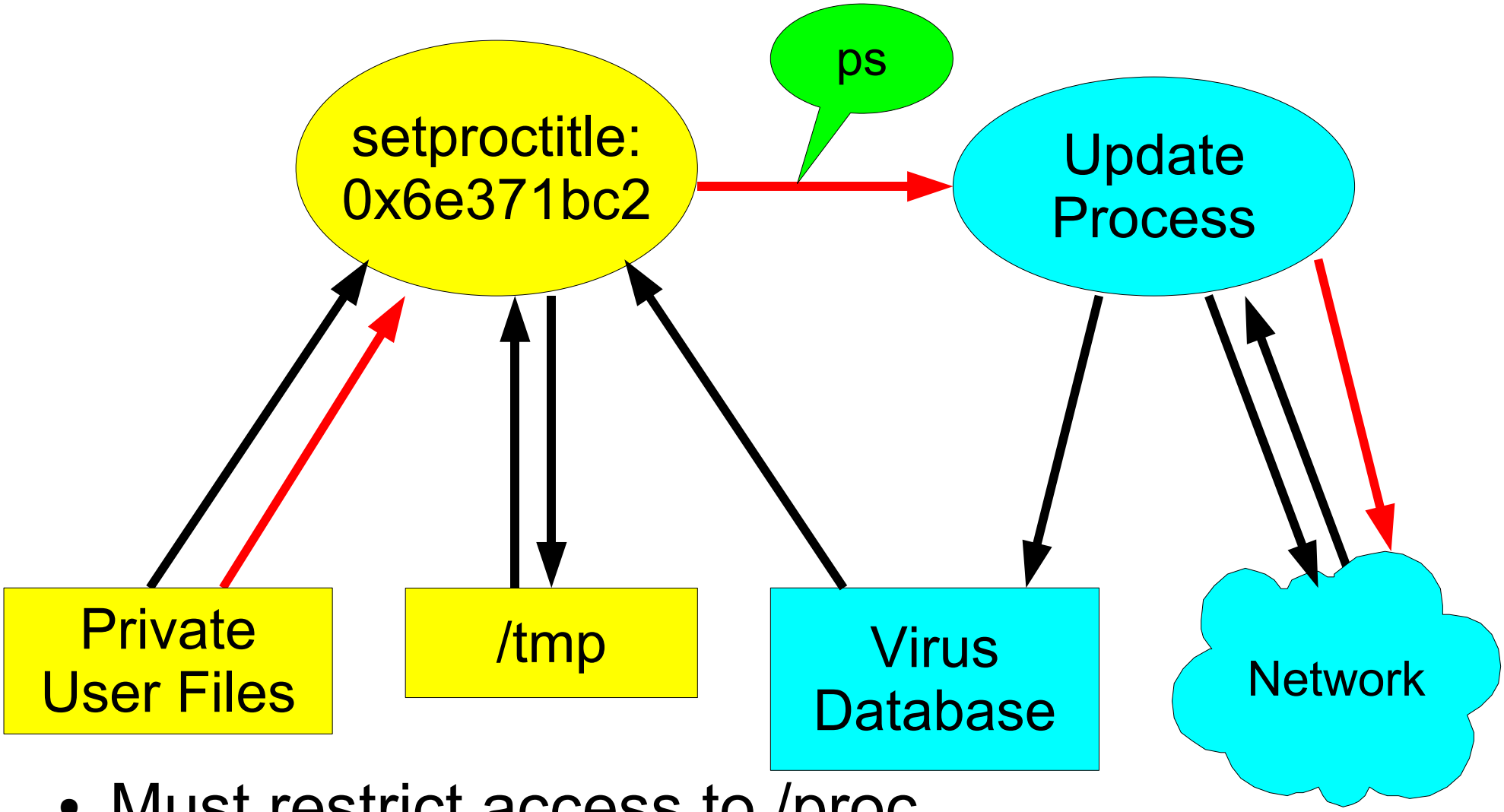


- Must run scanner with different UID

Buggy scanner leaks private data



- Must restrict access to /proc, ...

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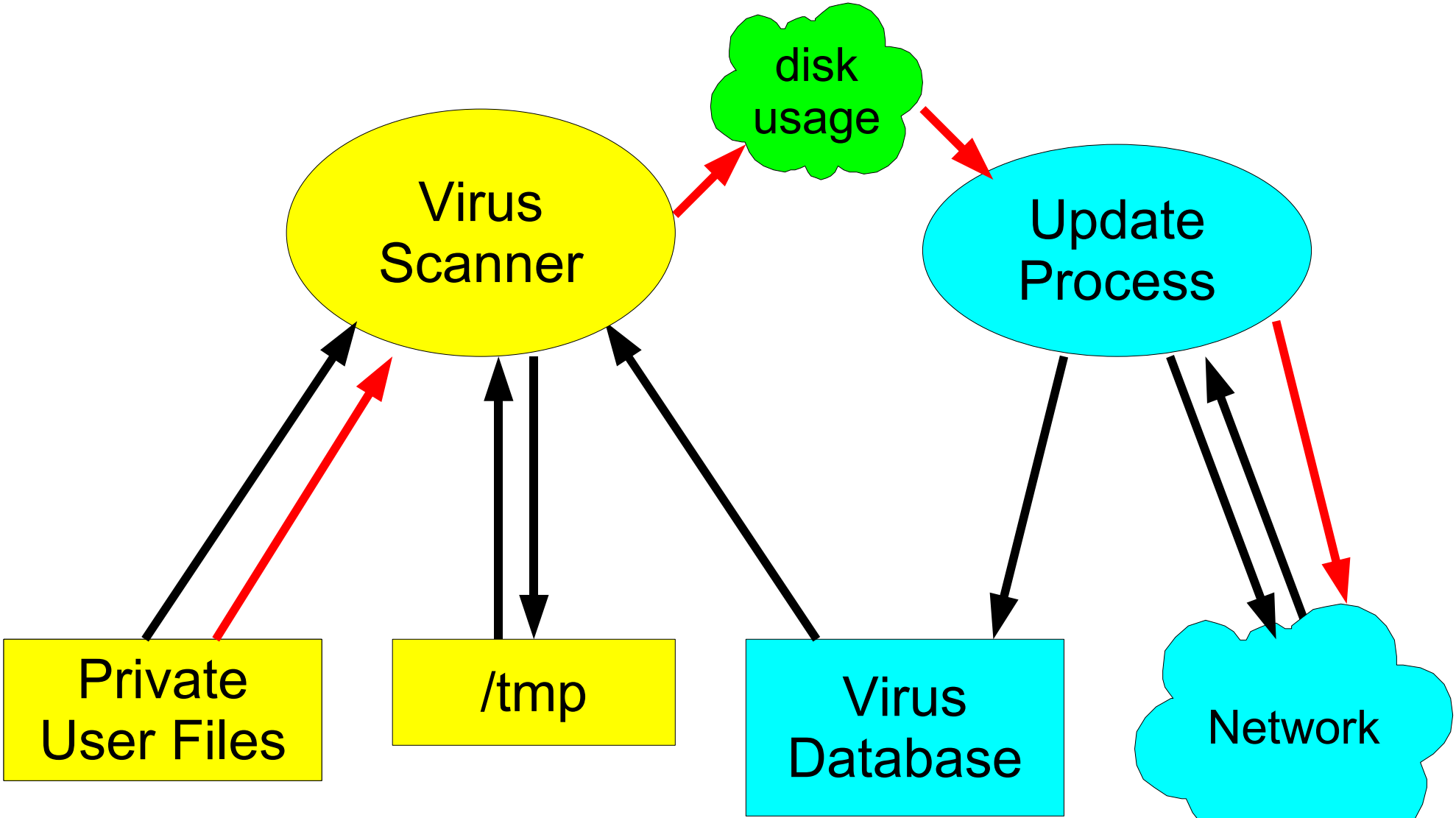
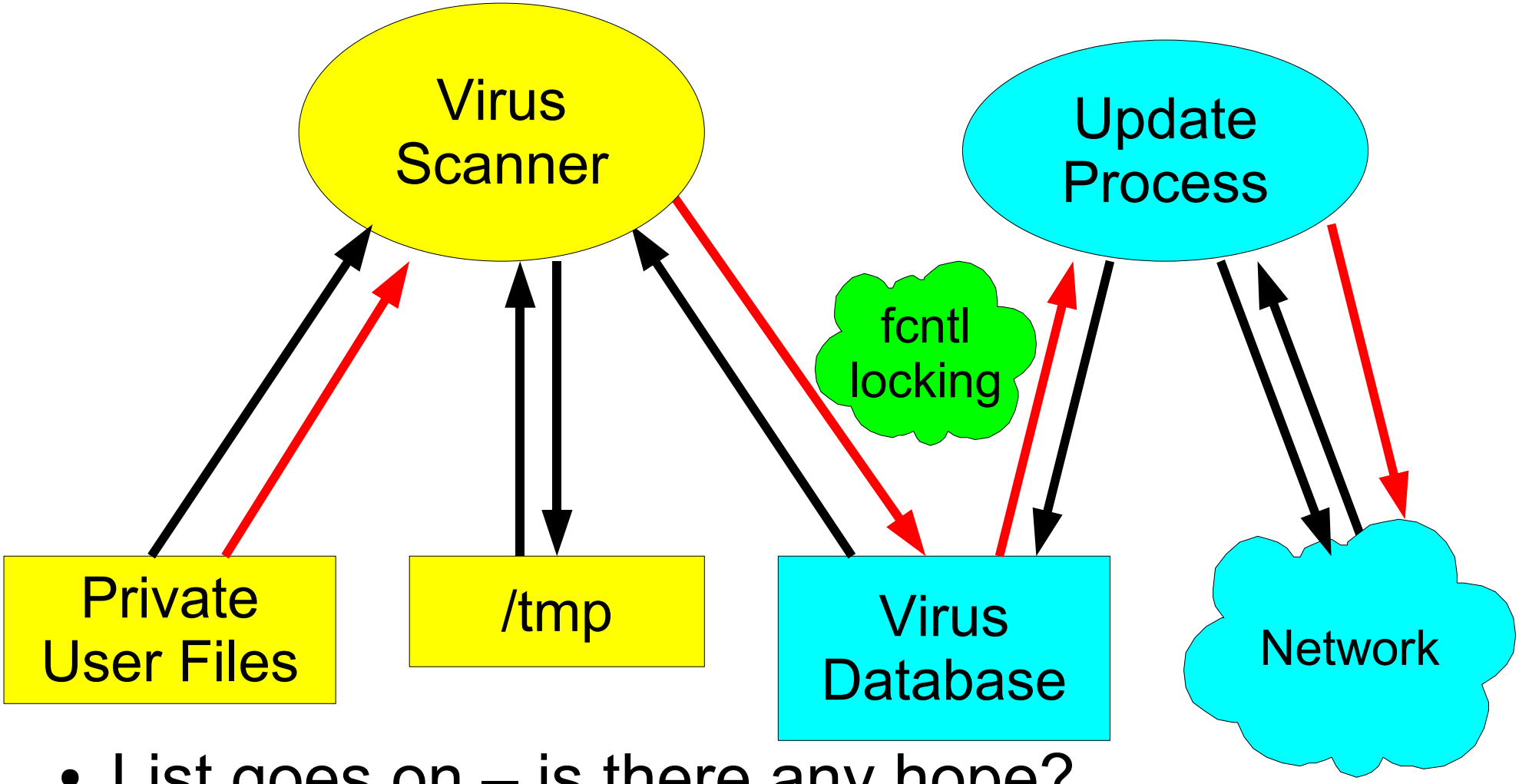


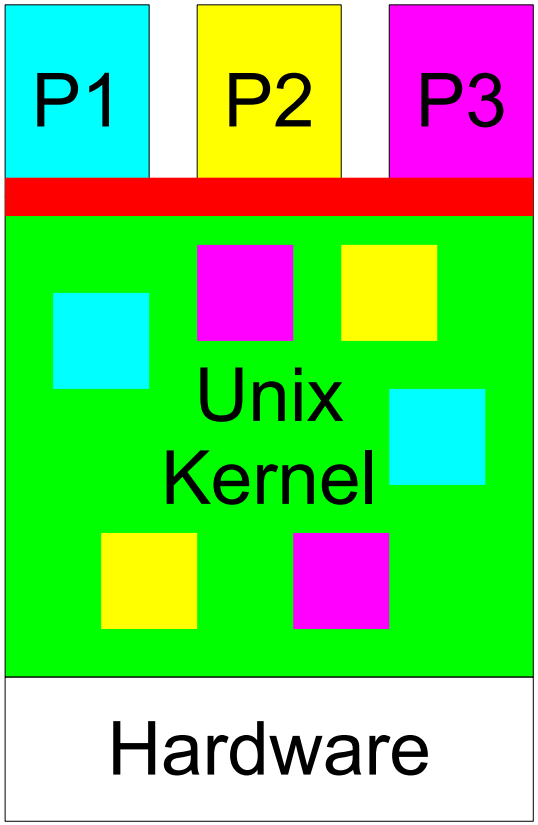
- Must restrict FS'es that virus scanner can write

Buggy scanner leaks private data



- List goes on – is there any hope?

What's going on?



Unix

- Kernel not designed to enforce these policies
- Retrofitting difficult
  - Need to track potentially any memory observed or modified by a system call!
  - Hard to even enumerate

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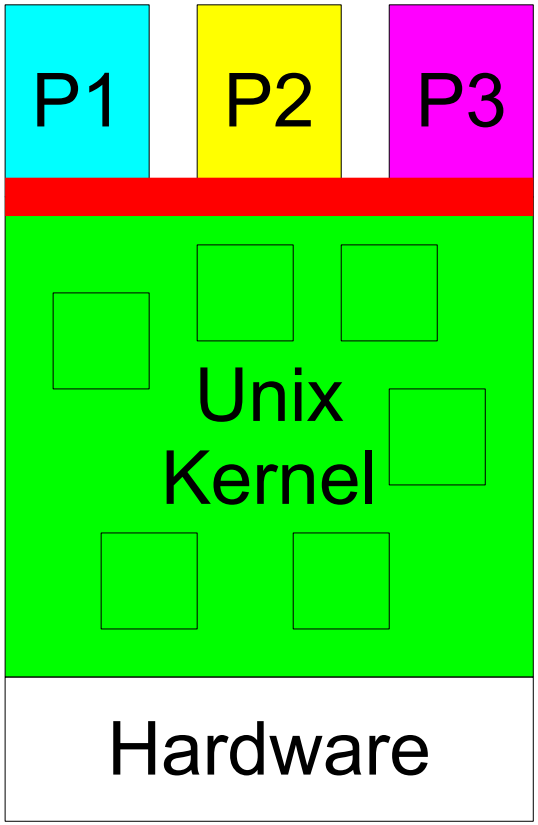

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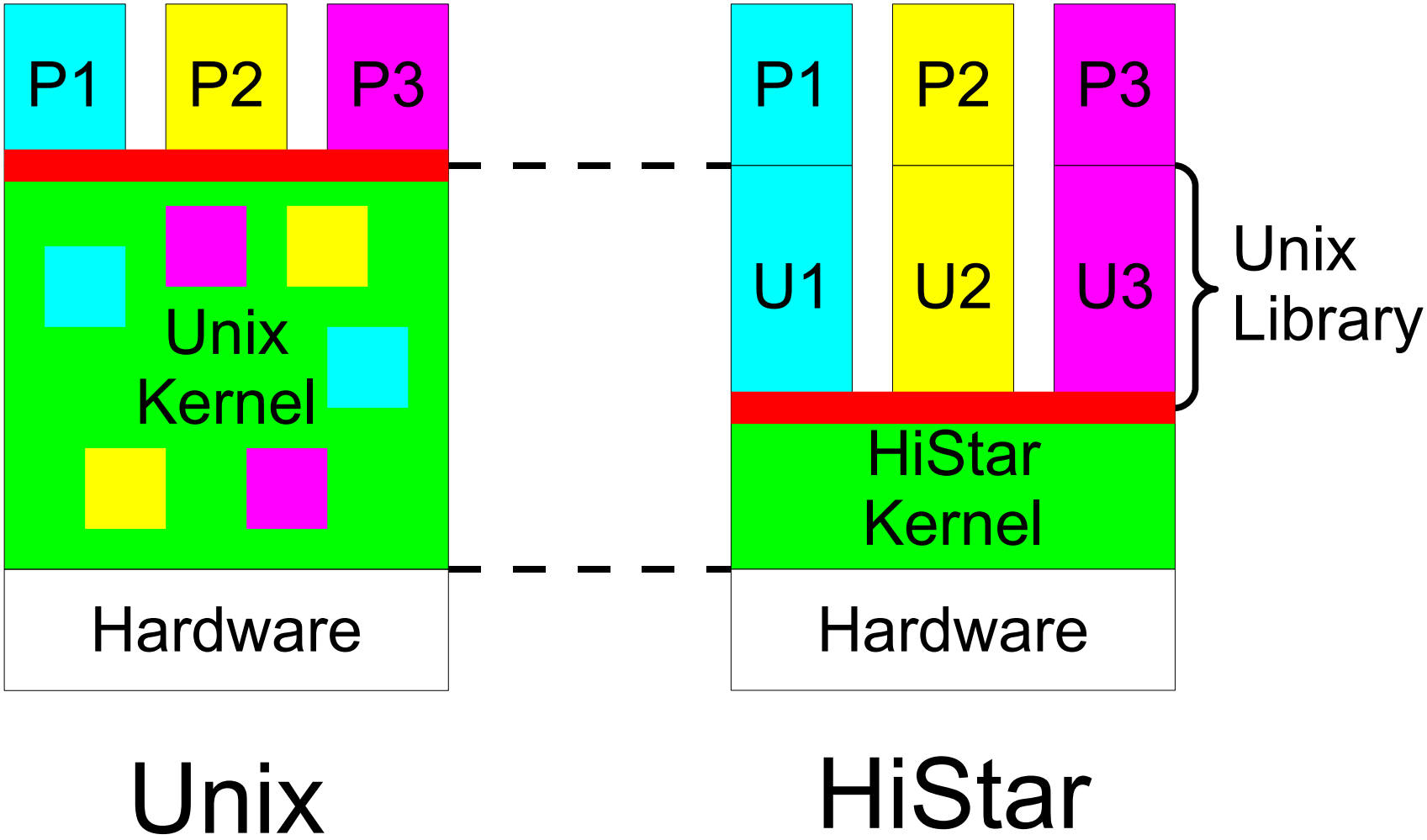
HiStar Solution

- Make all state explicit, track all communication

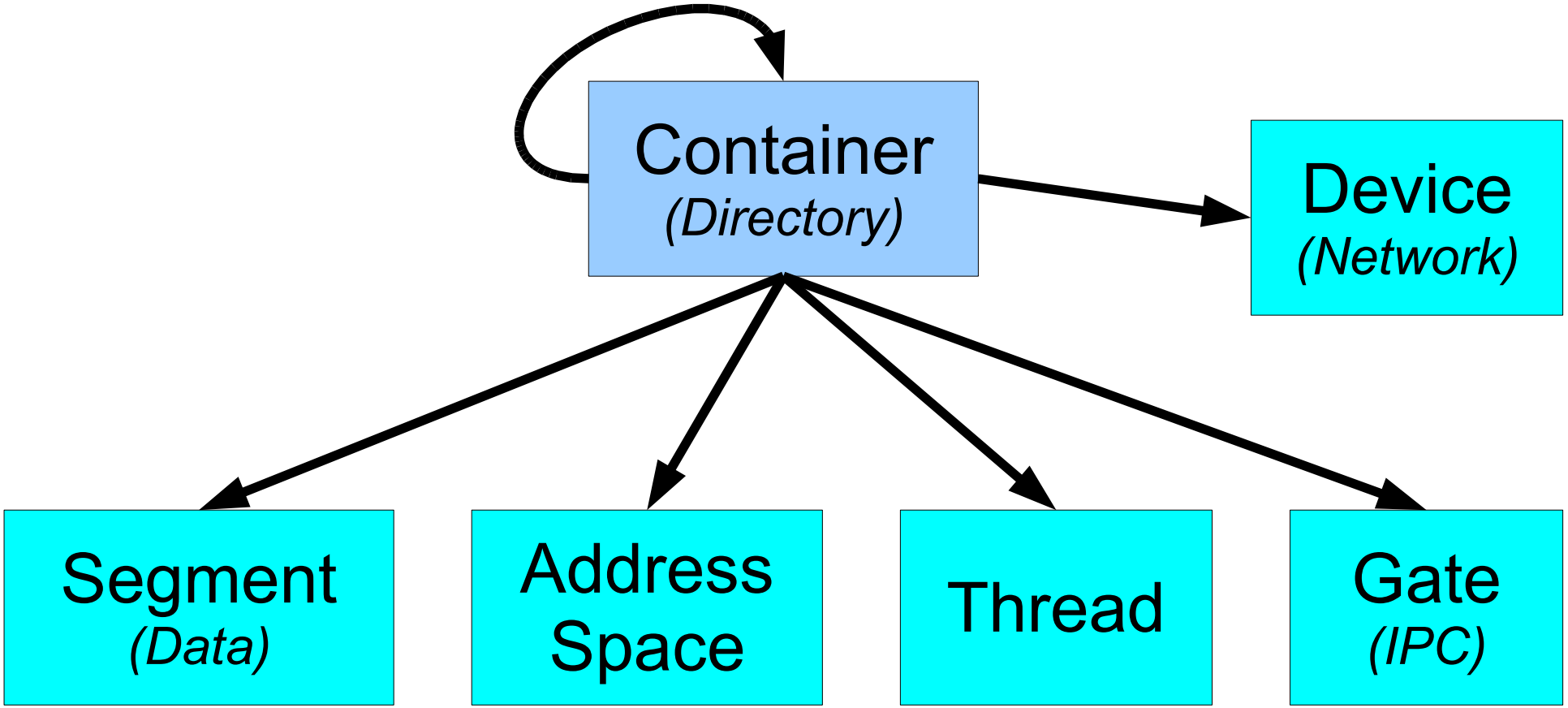


HiStar design

- Narrow kernel interface
  - Simple objects with simple, well-defined operations
  - Strictly control information flow for every operation
  - Overall approach: *make everything explicit*

- Unix support implemented as user-level library
  - Composes safe kernel operations to implement Unix
  - Composing is safe, since information flow is transitive
  - Provides control over the gamut of Unix channels

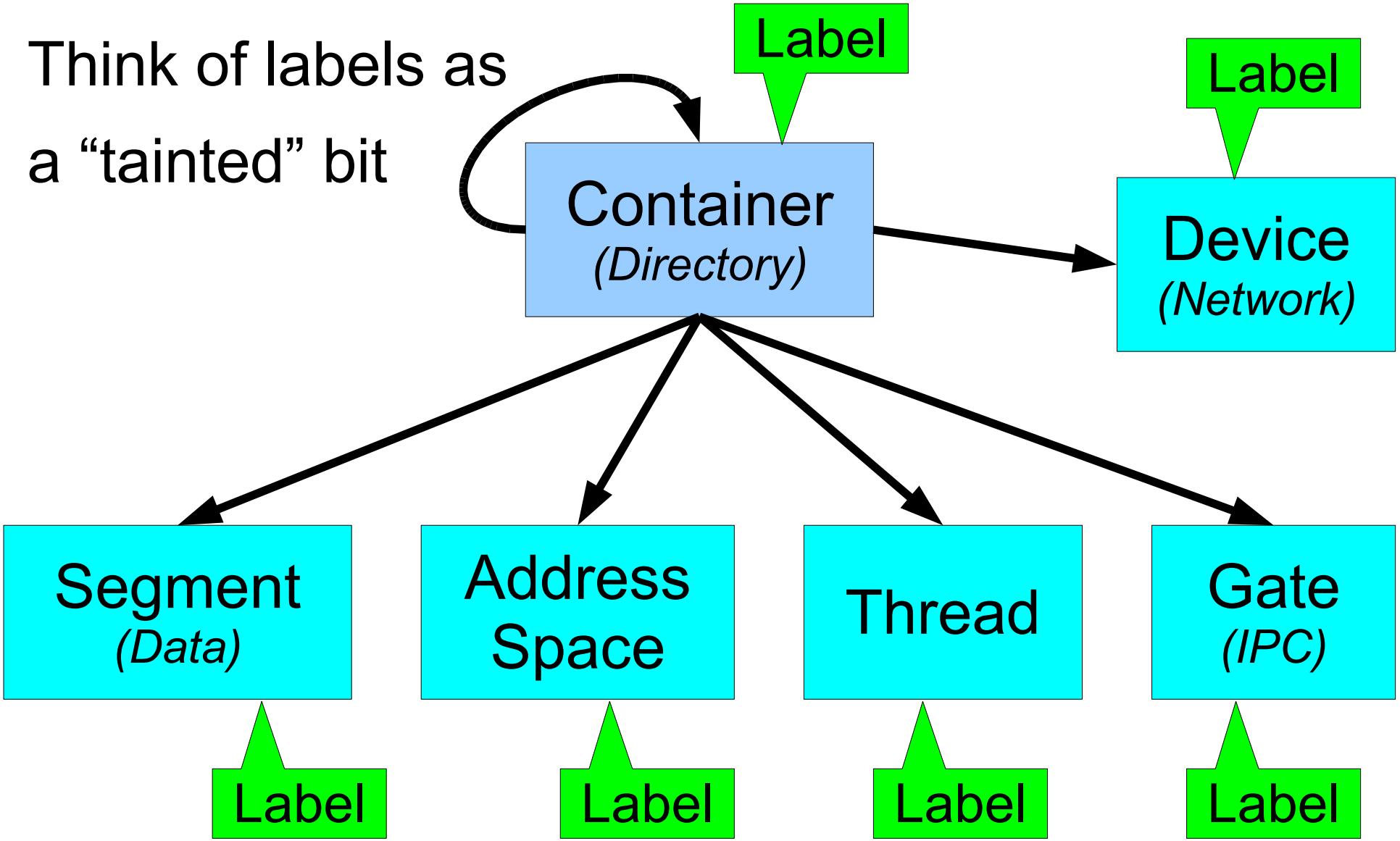
HiStar kernel objects



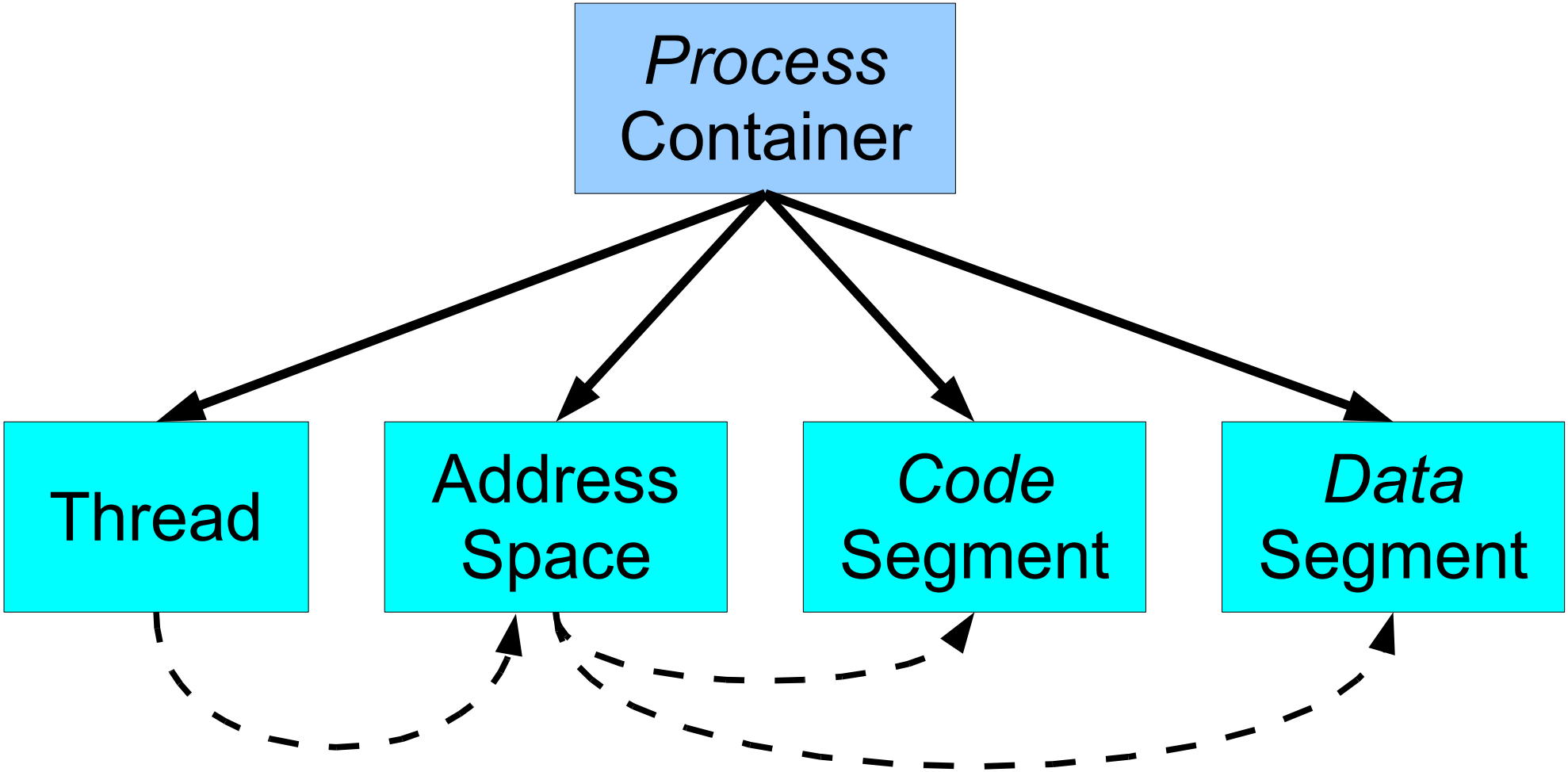
HiStar kernel objects

Think of labels as

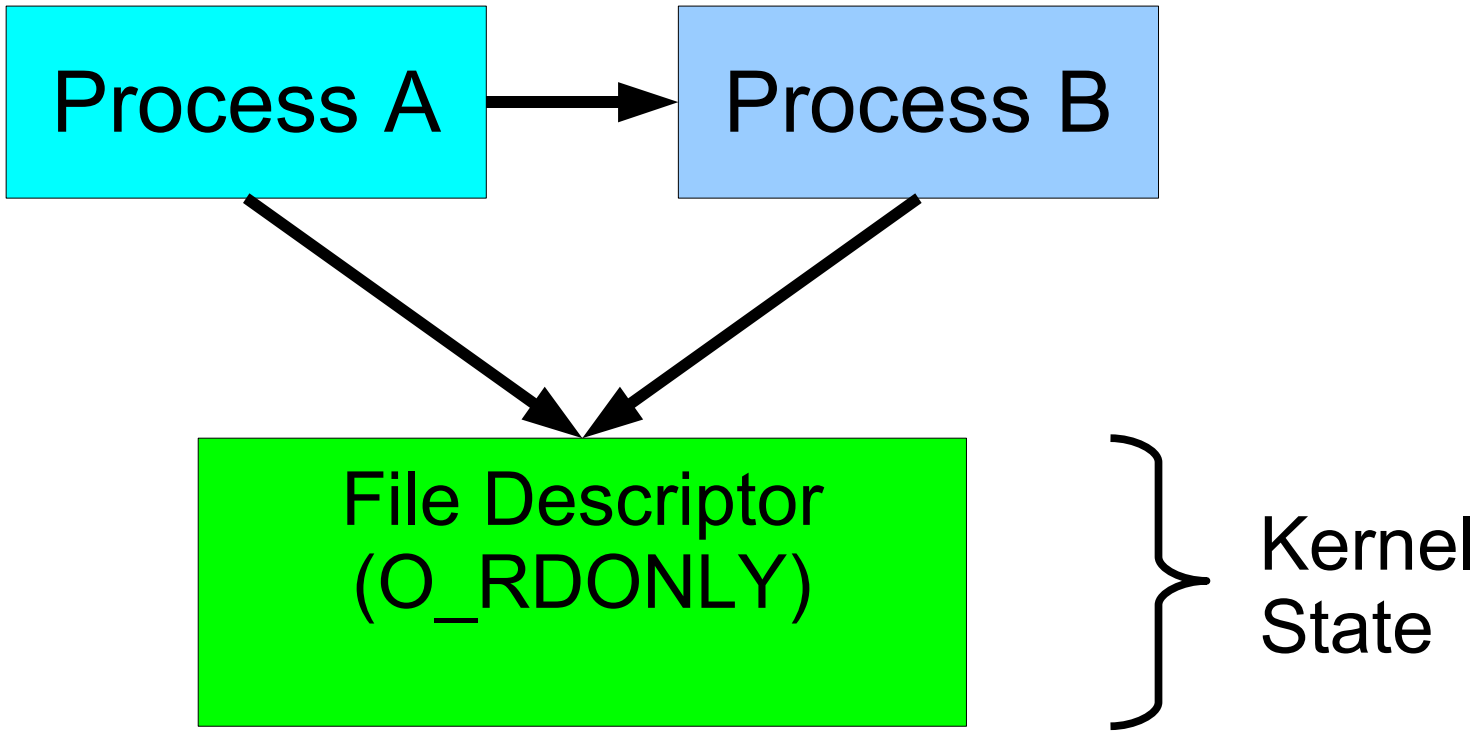
a “tainted” bit



HiStar: Unix process

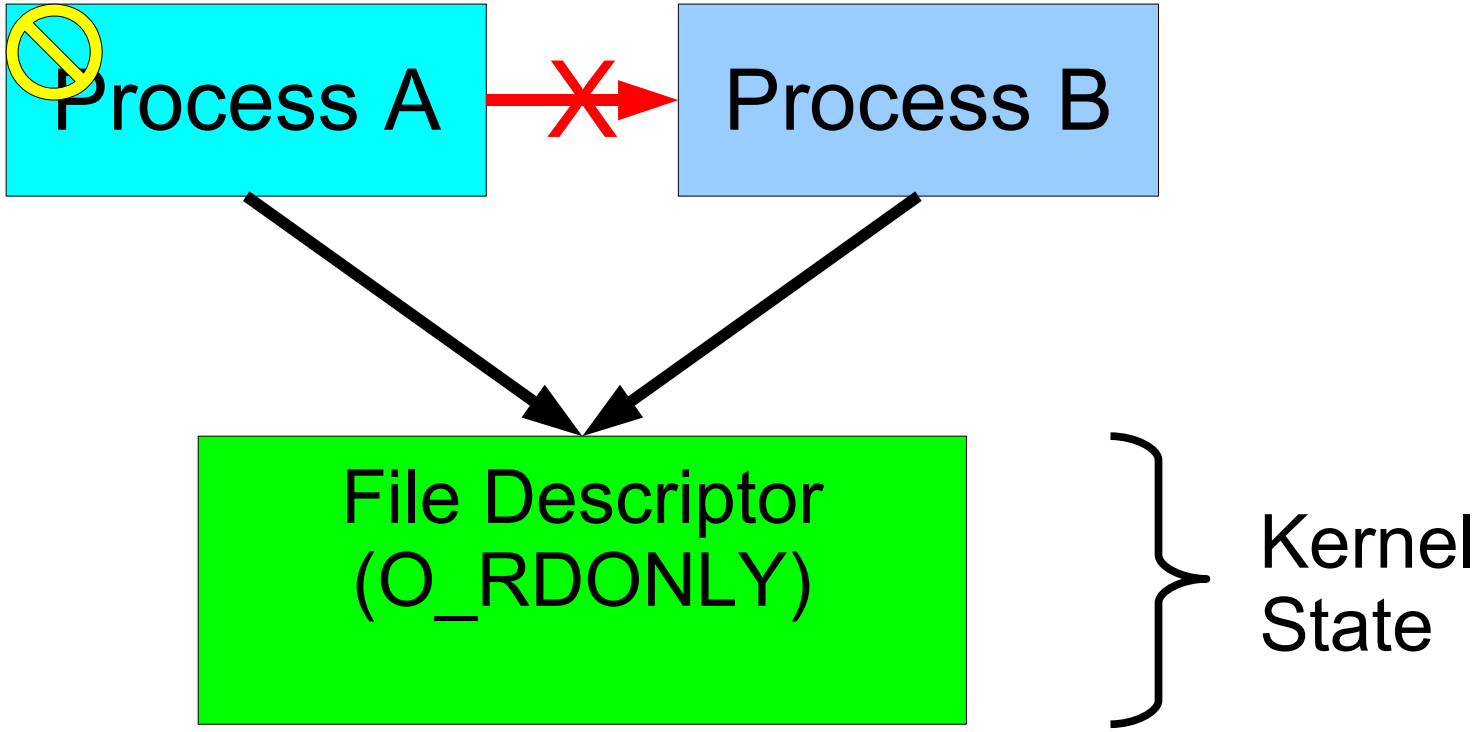


Unix File Descriptors



Unix File Descriptors

- Tainted process only talks to other tainted procs



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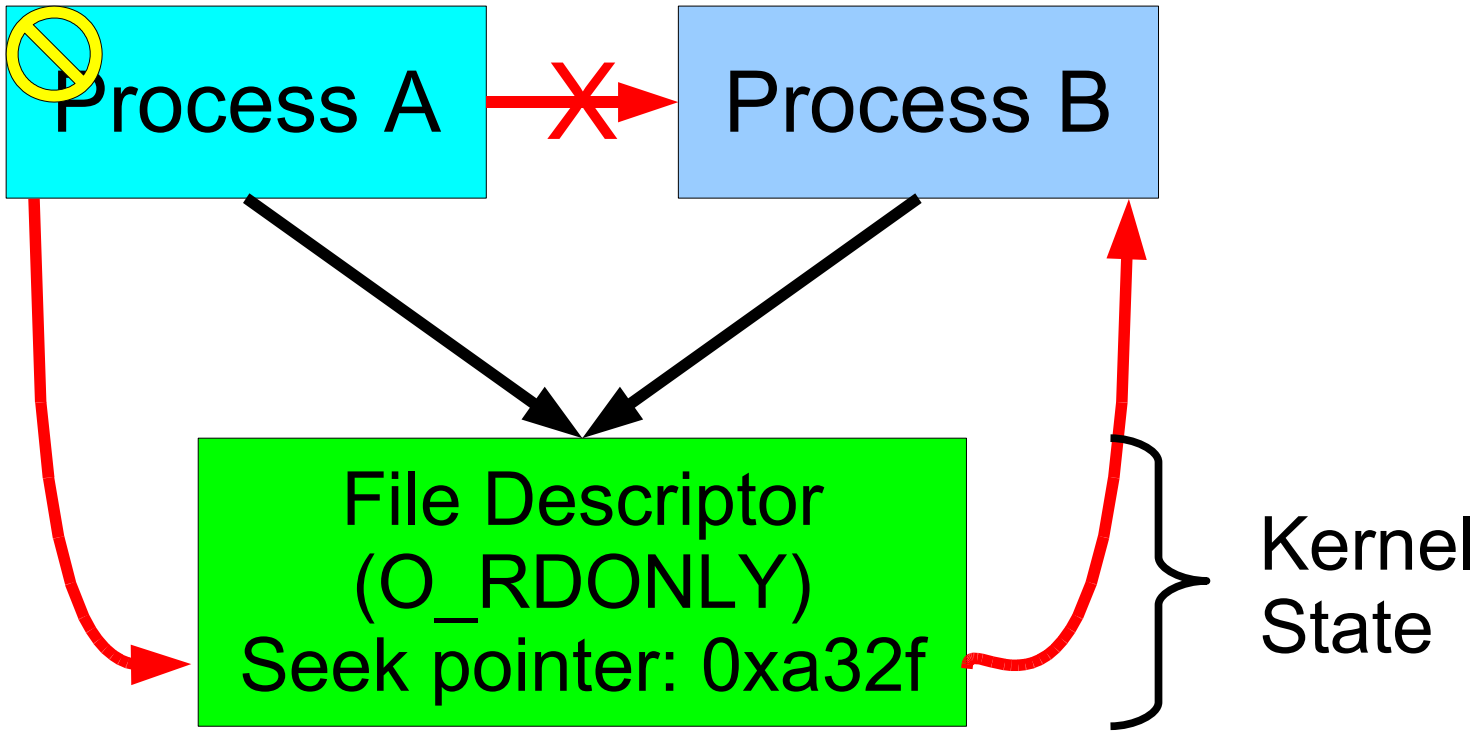
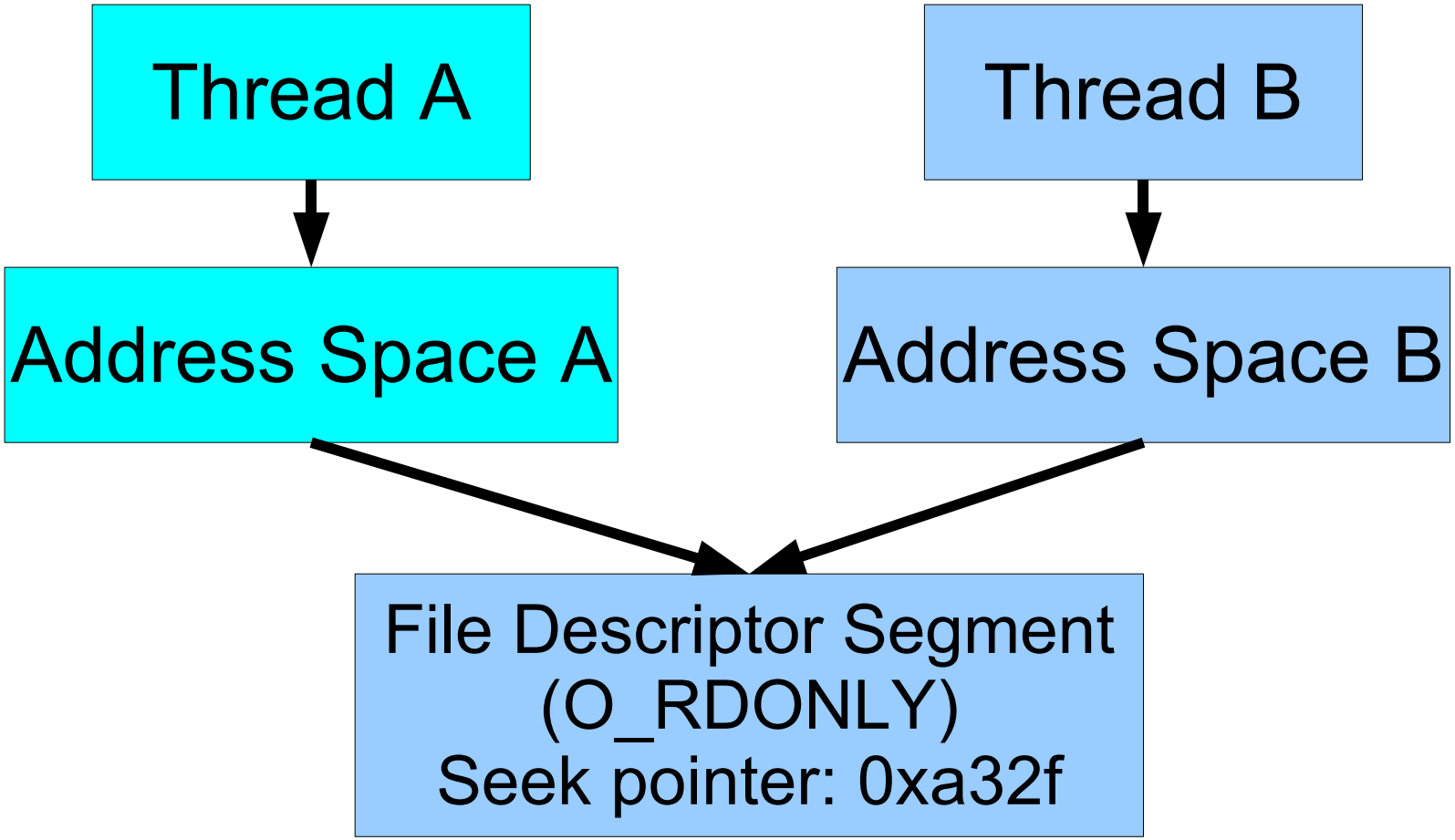


- Lots of shared state in kernel, easy to miss

HiStar File Descriptors



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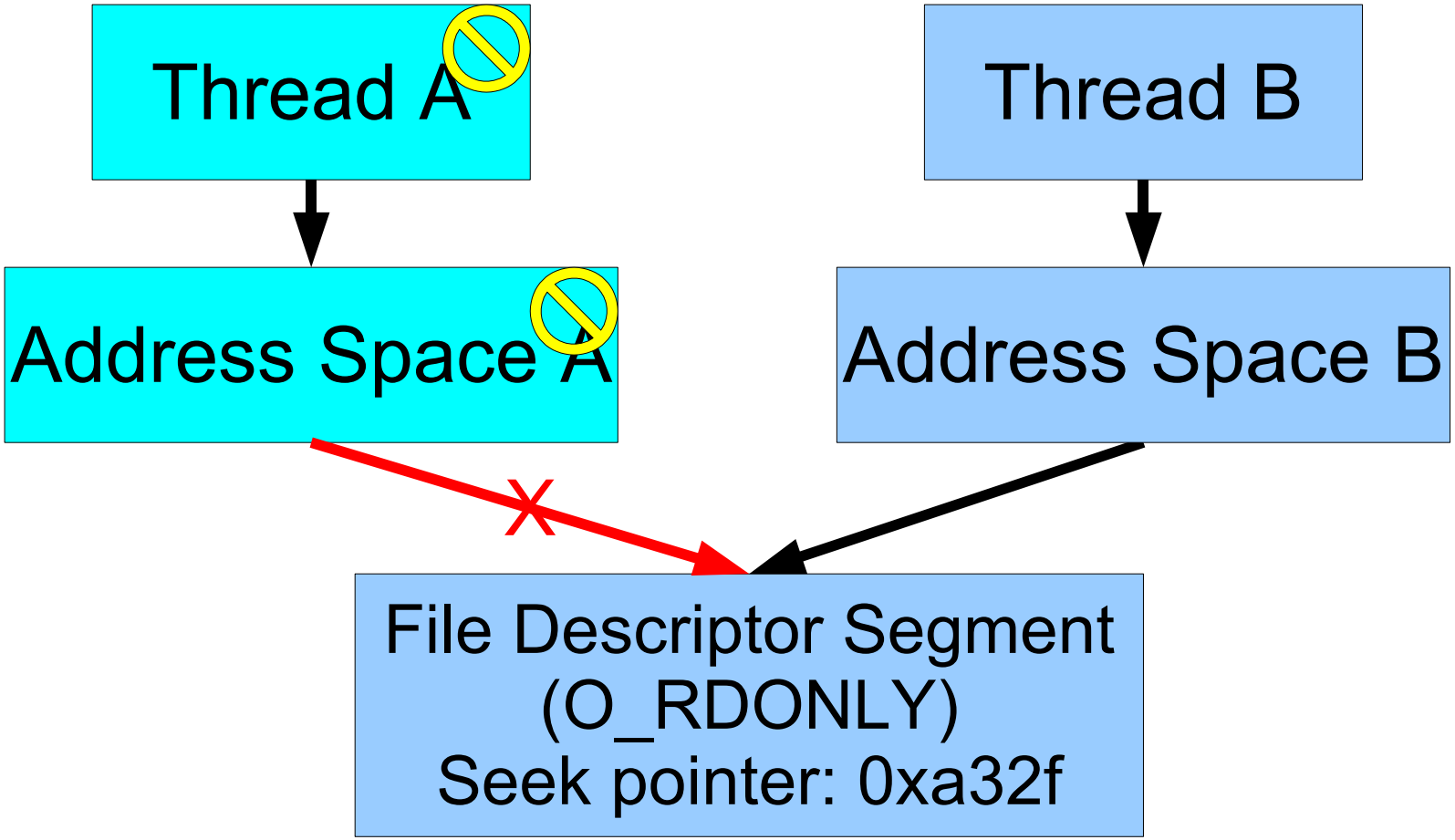
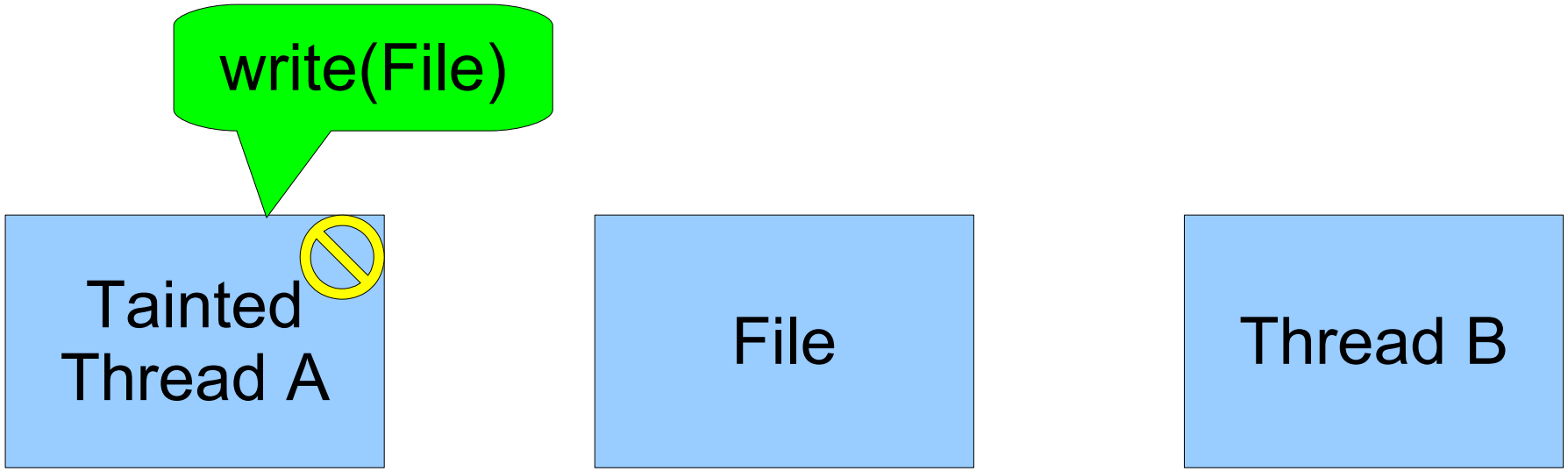


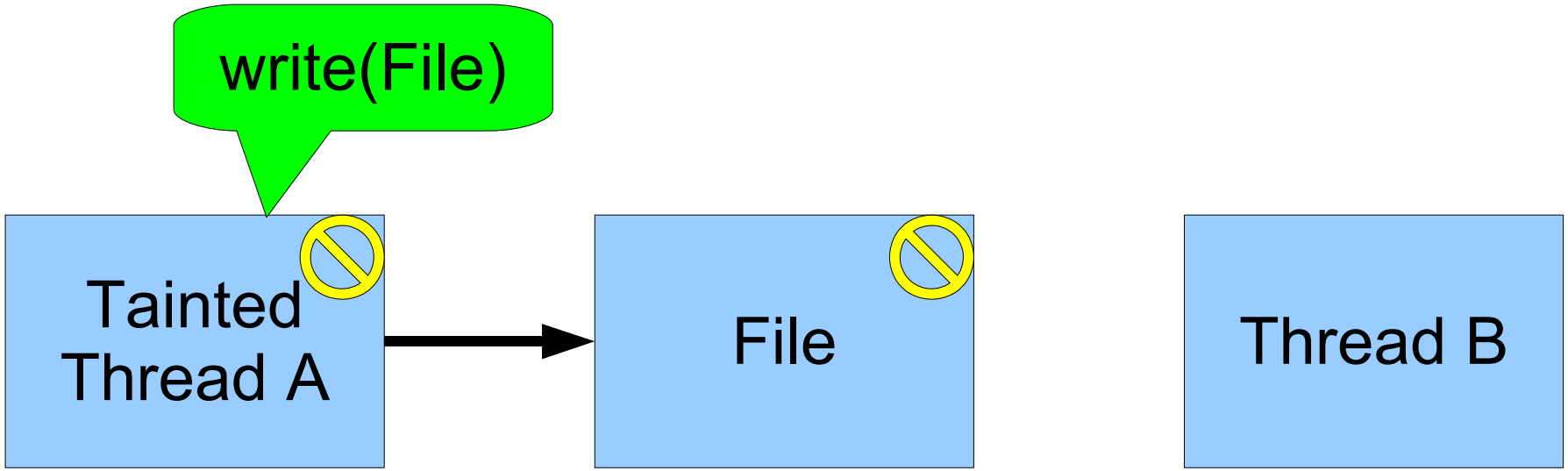
- All shared state is now explicitly labeled
- **Reduce problem to object read/write checks**

Taint Tracking Strawman



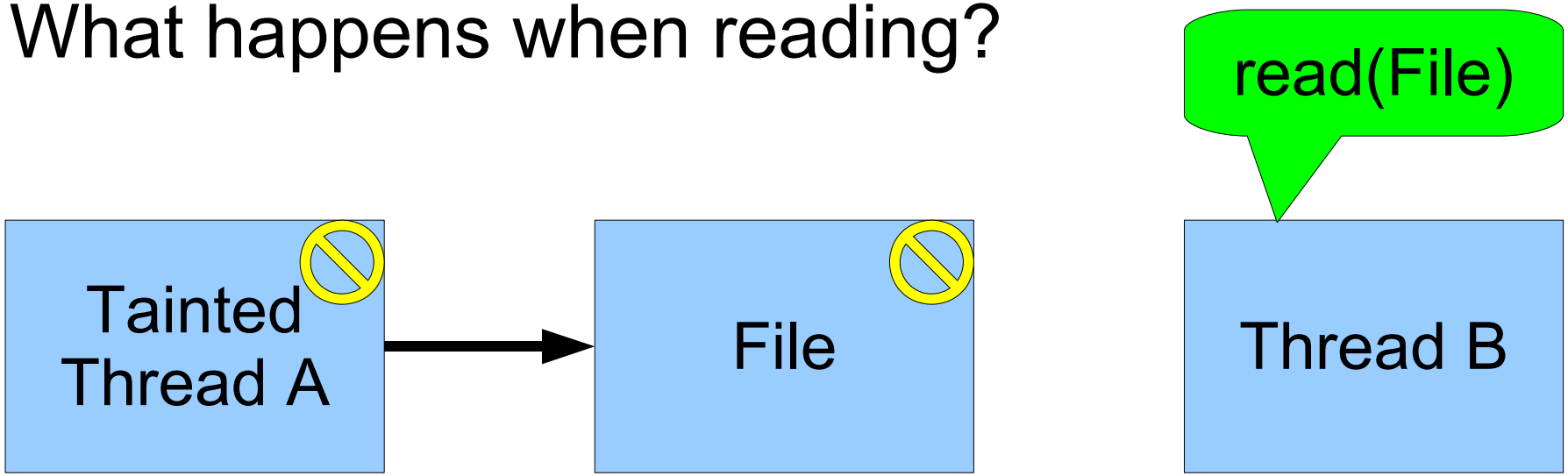
Taint Tracking Strawman

- Propagate taint when writing to file



Taint Tracking Strawman

- Propagate taint when writing to file
- What happens when reading?



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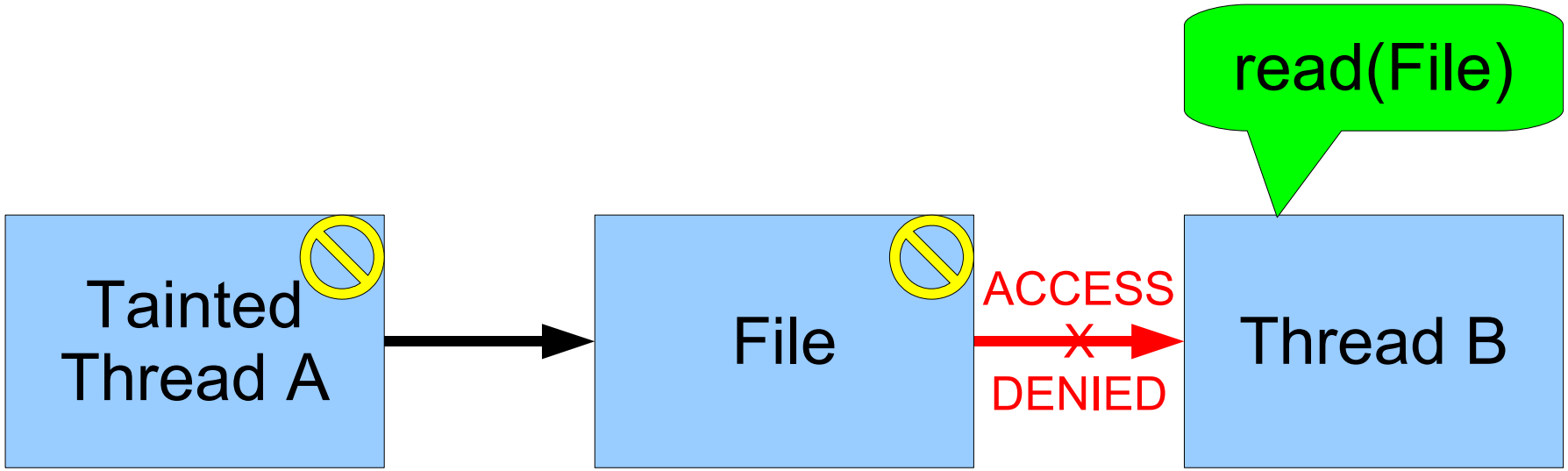
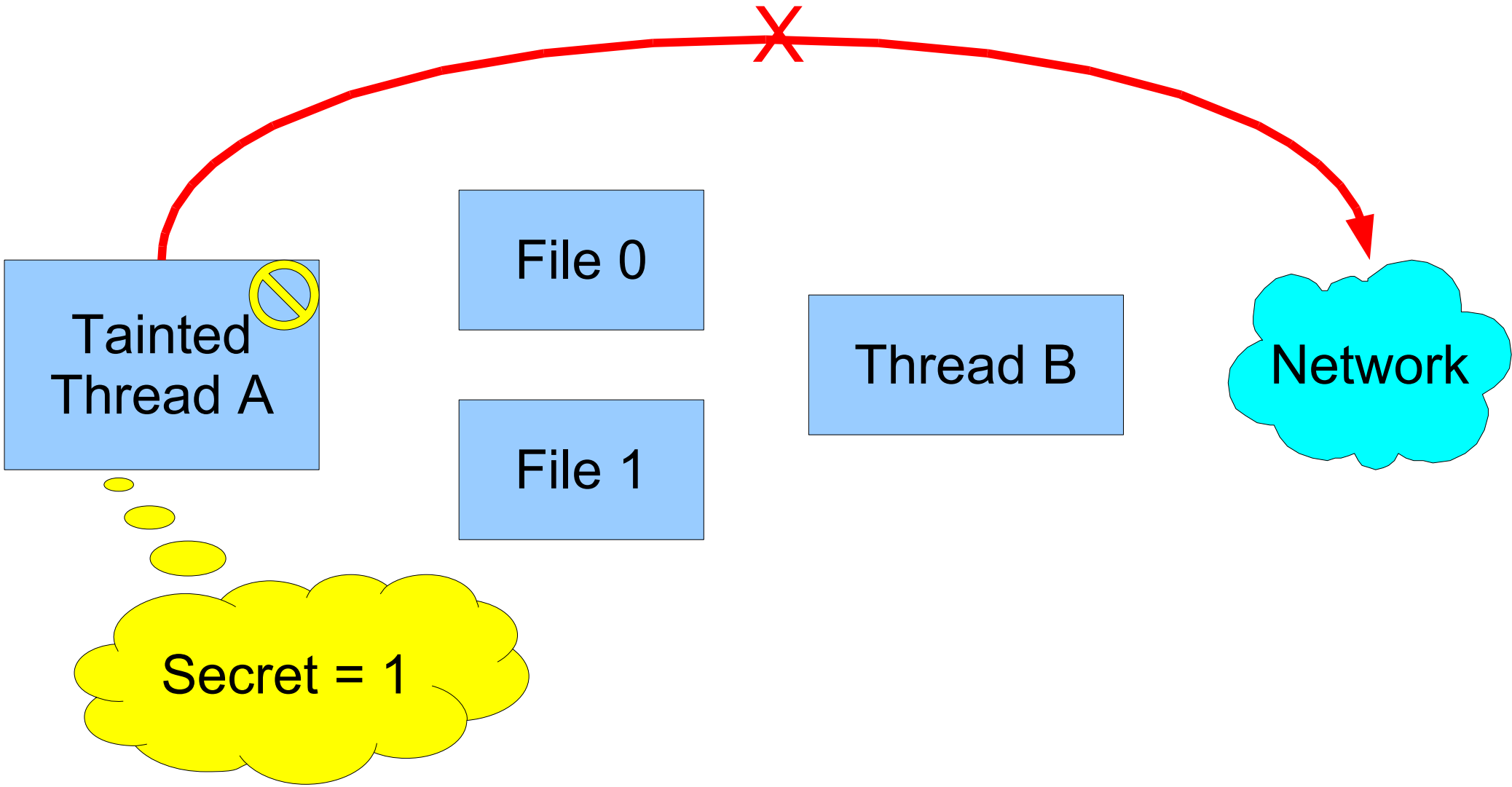


Strawman has Covert Channel



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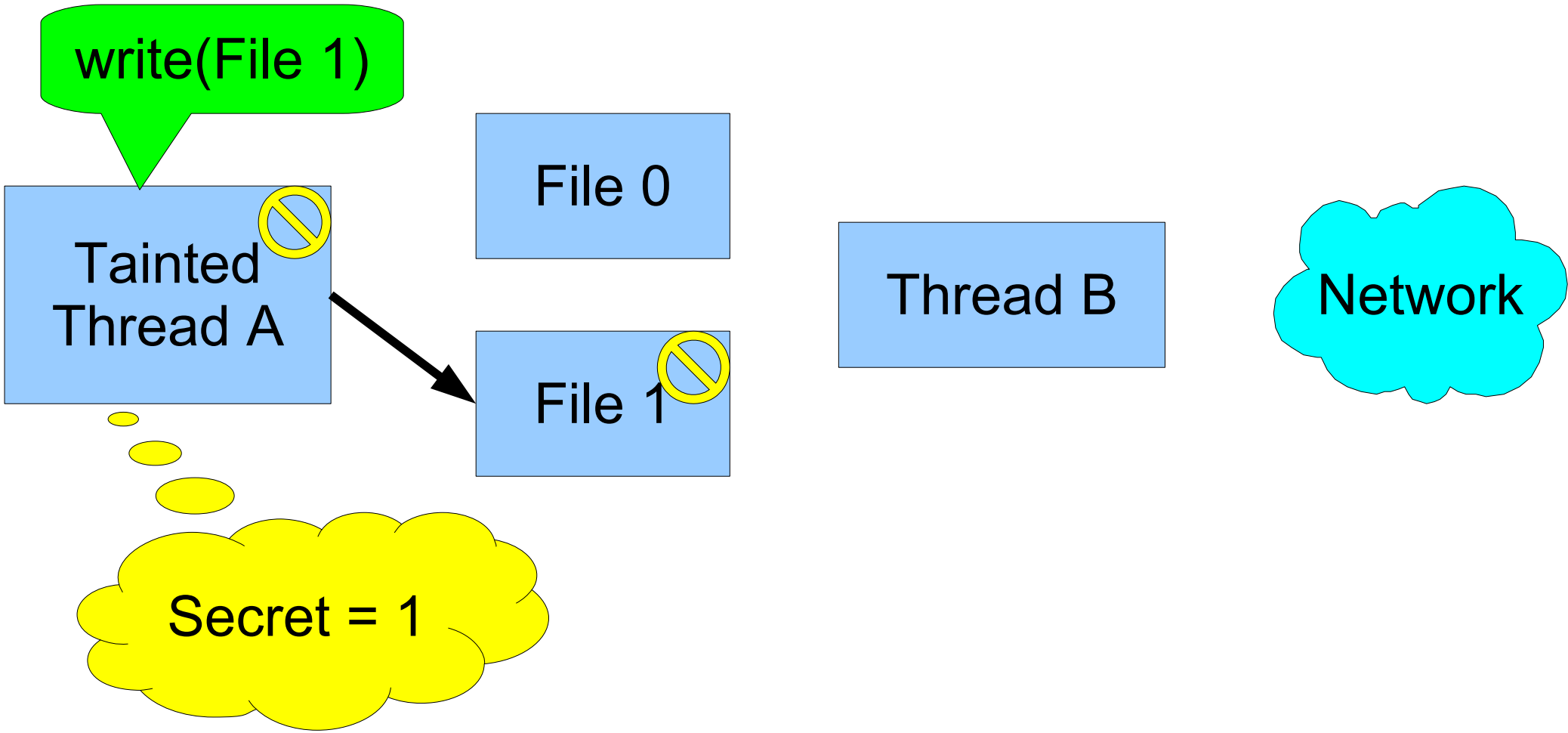

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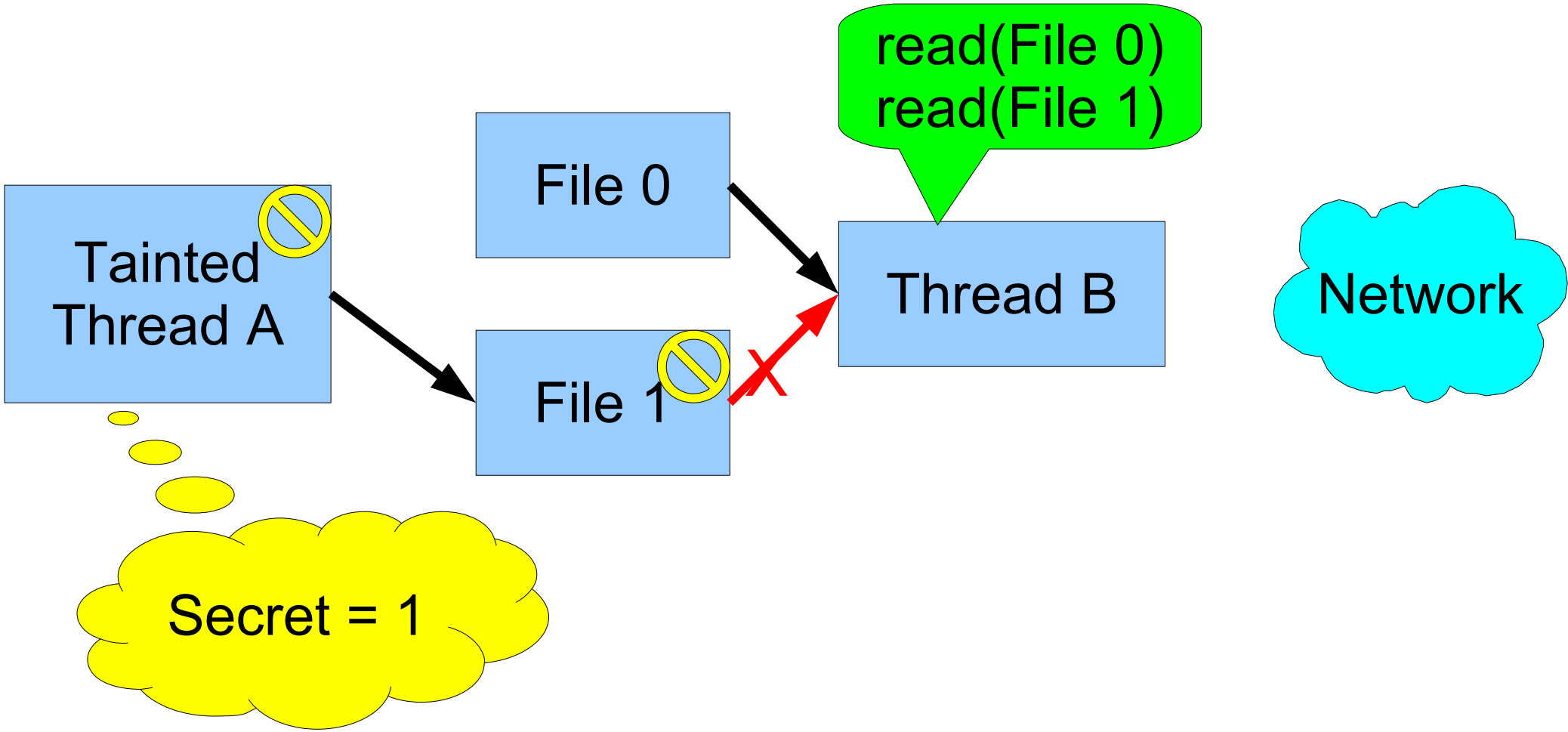

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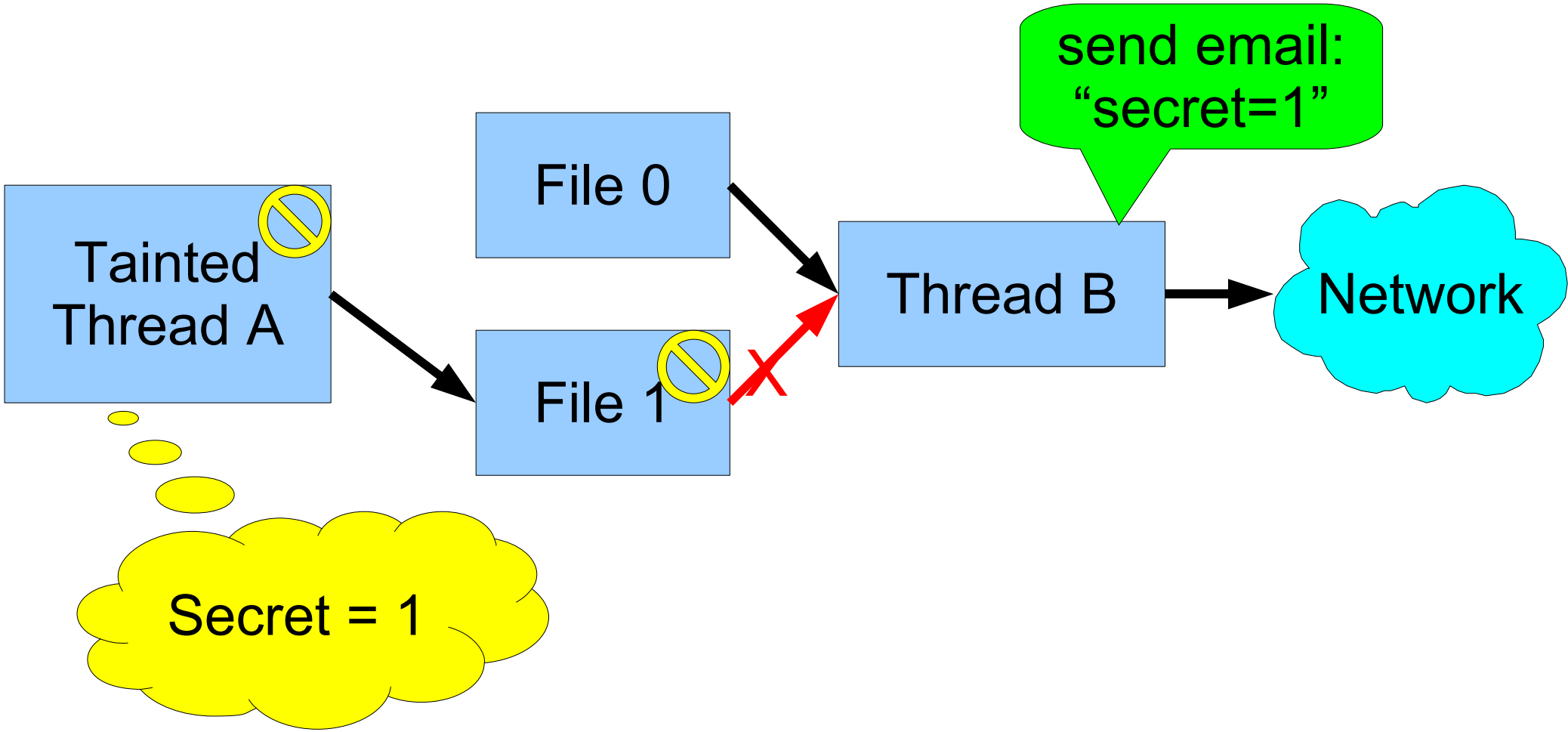

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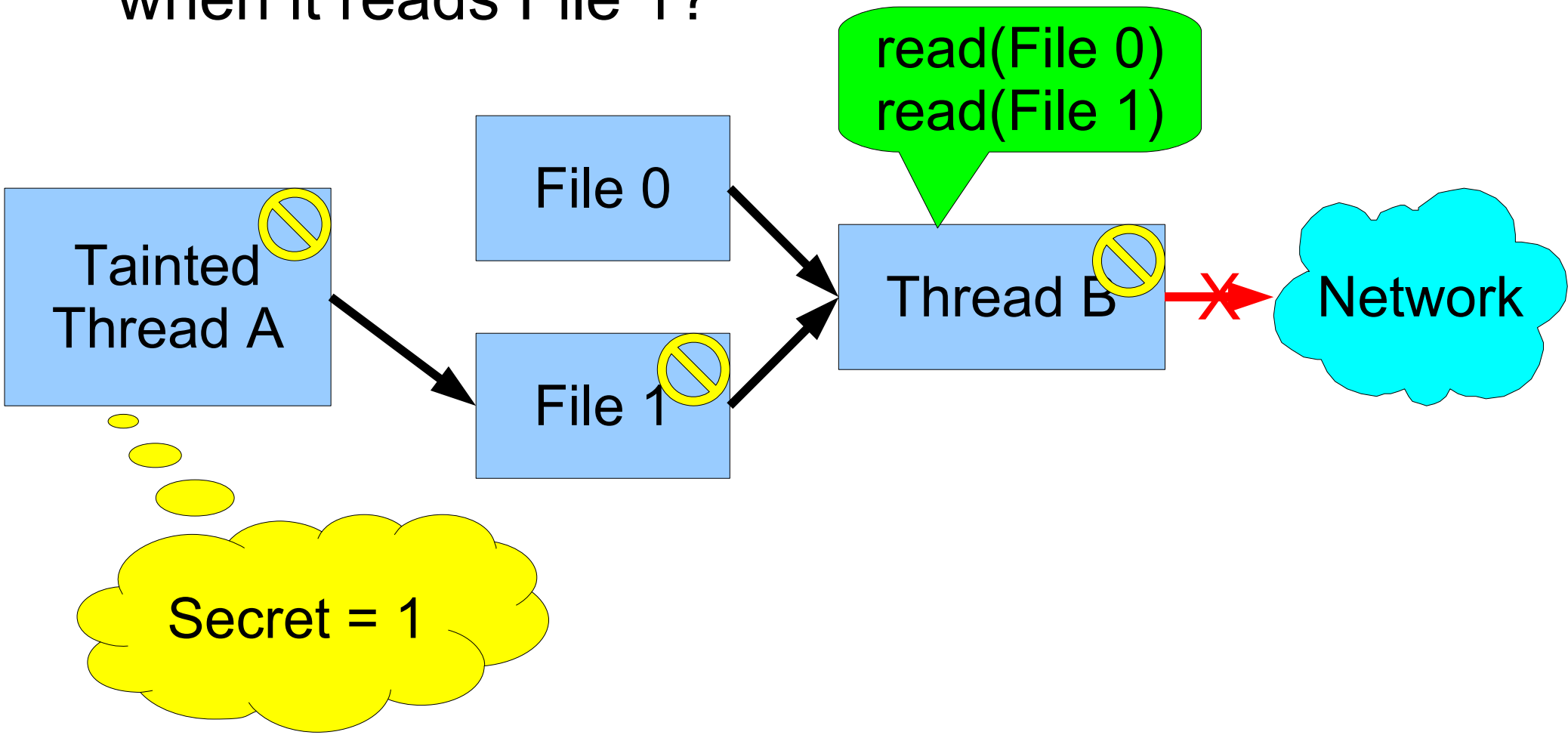

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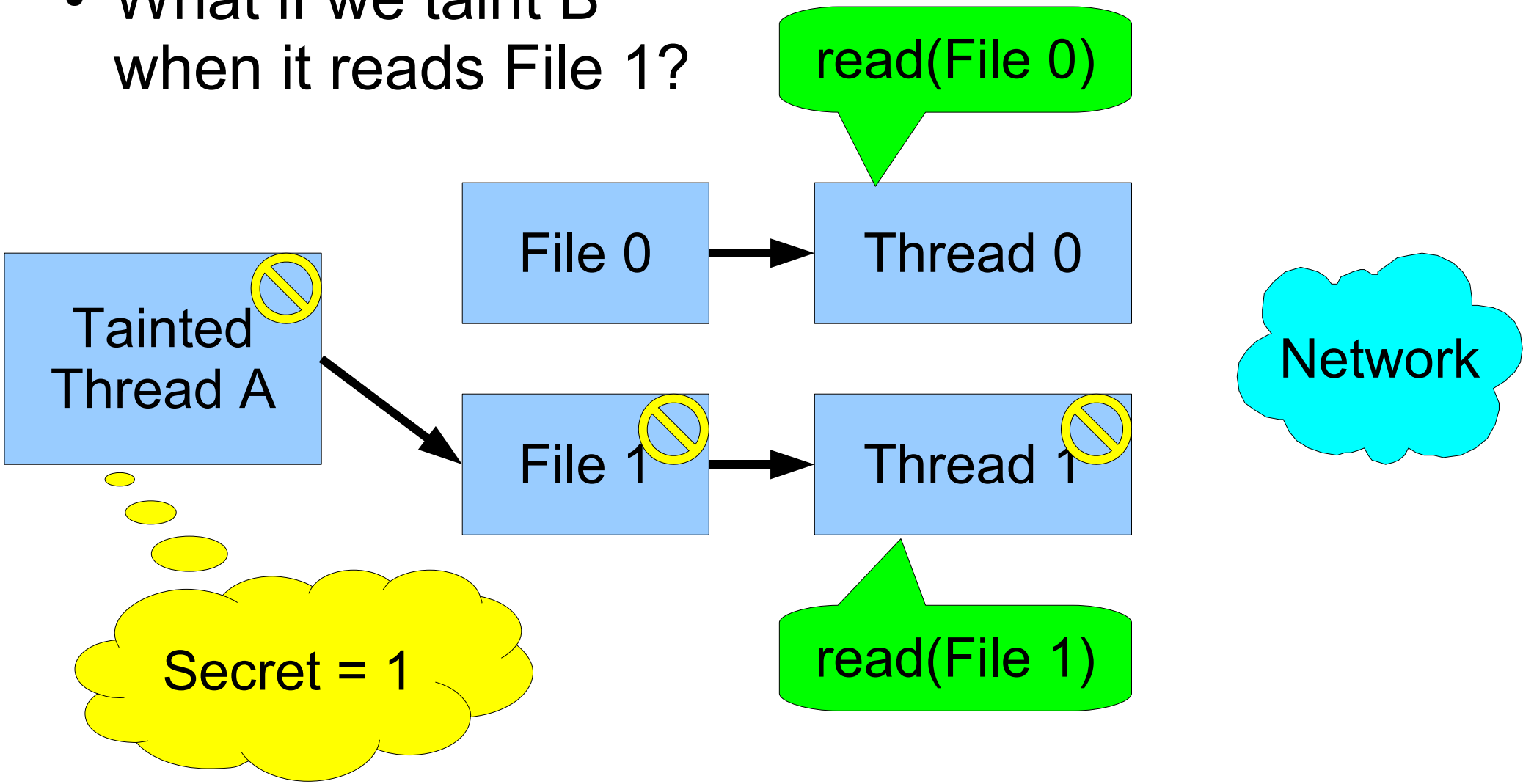

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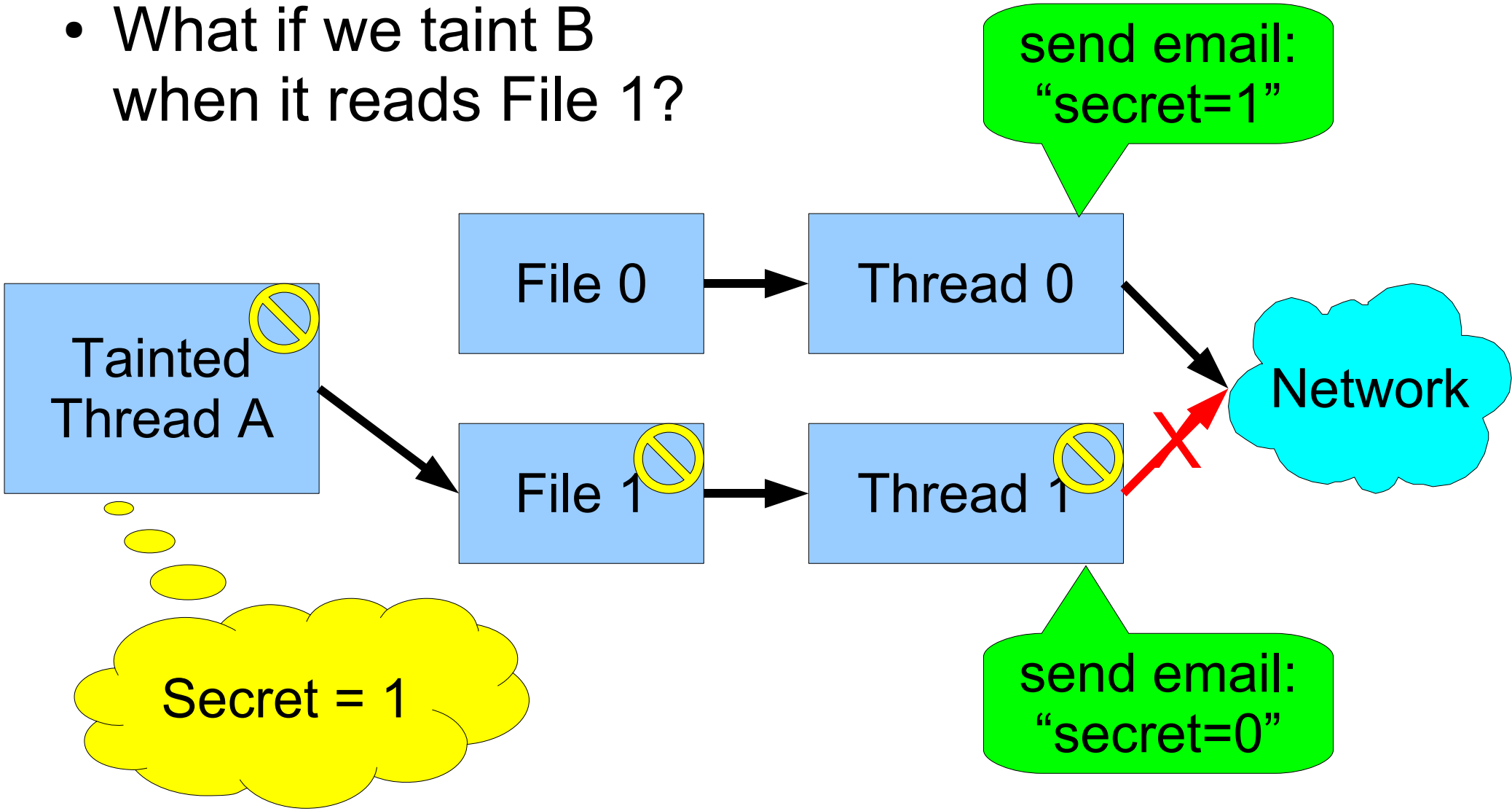
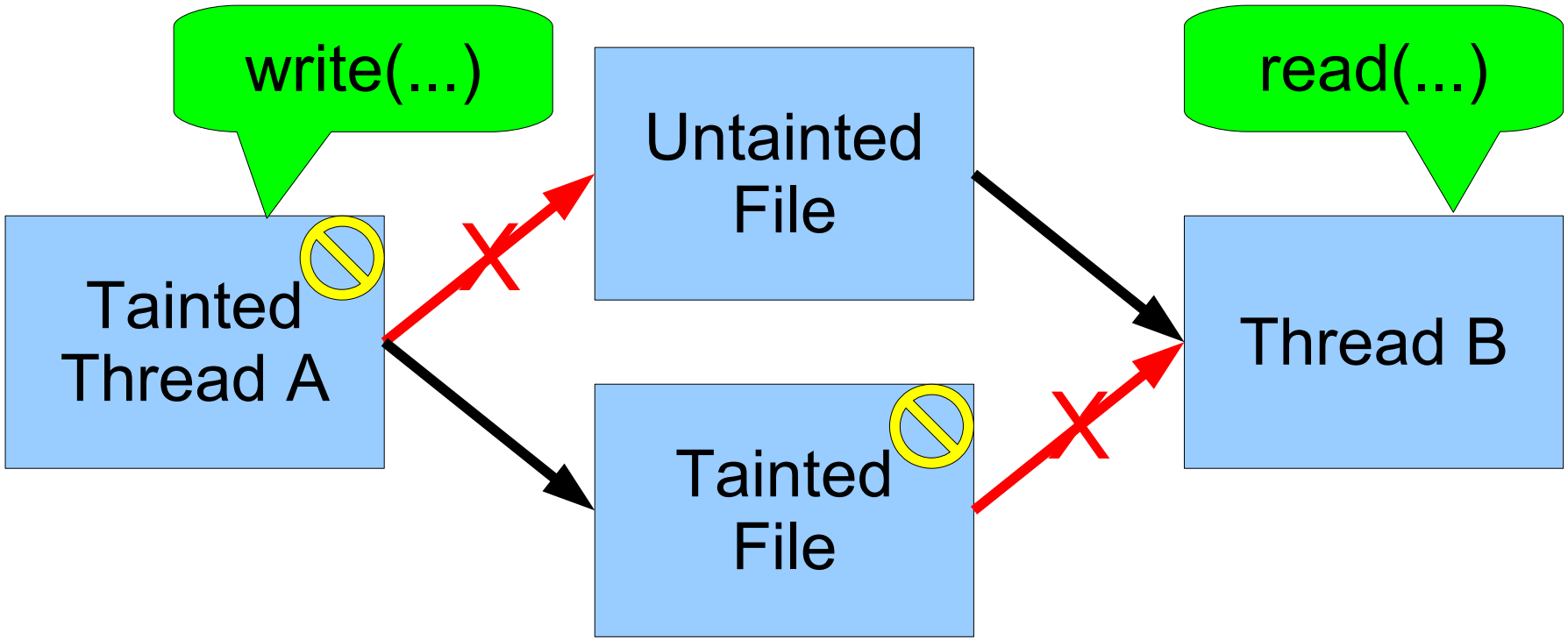


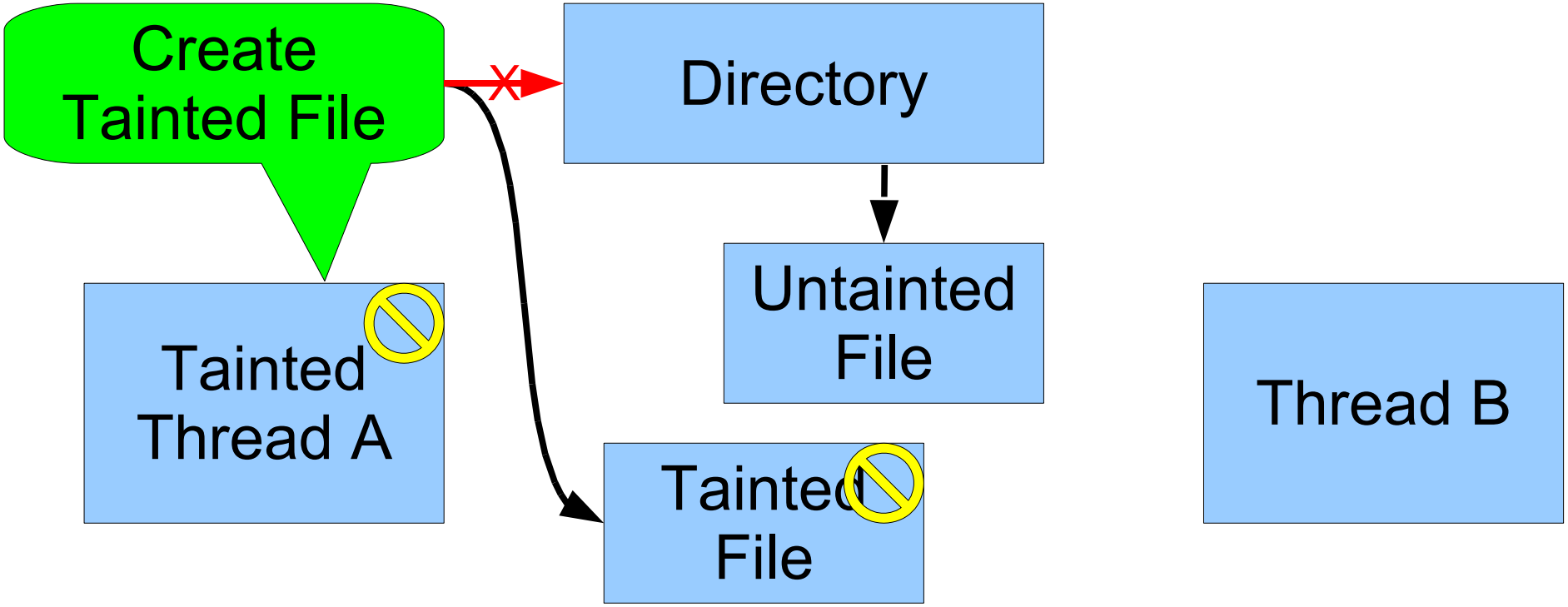
HiStar: Immutable File Labels

- Label (taint level) is state that must be tracked
- Immutable labels solve this problem!



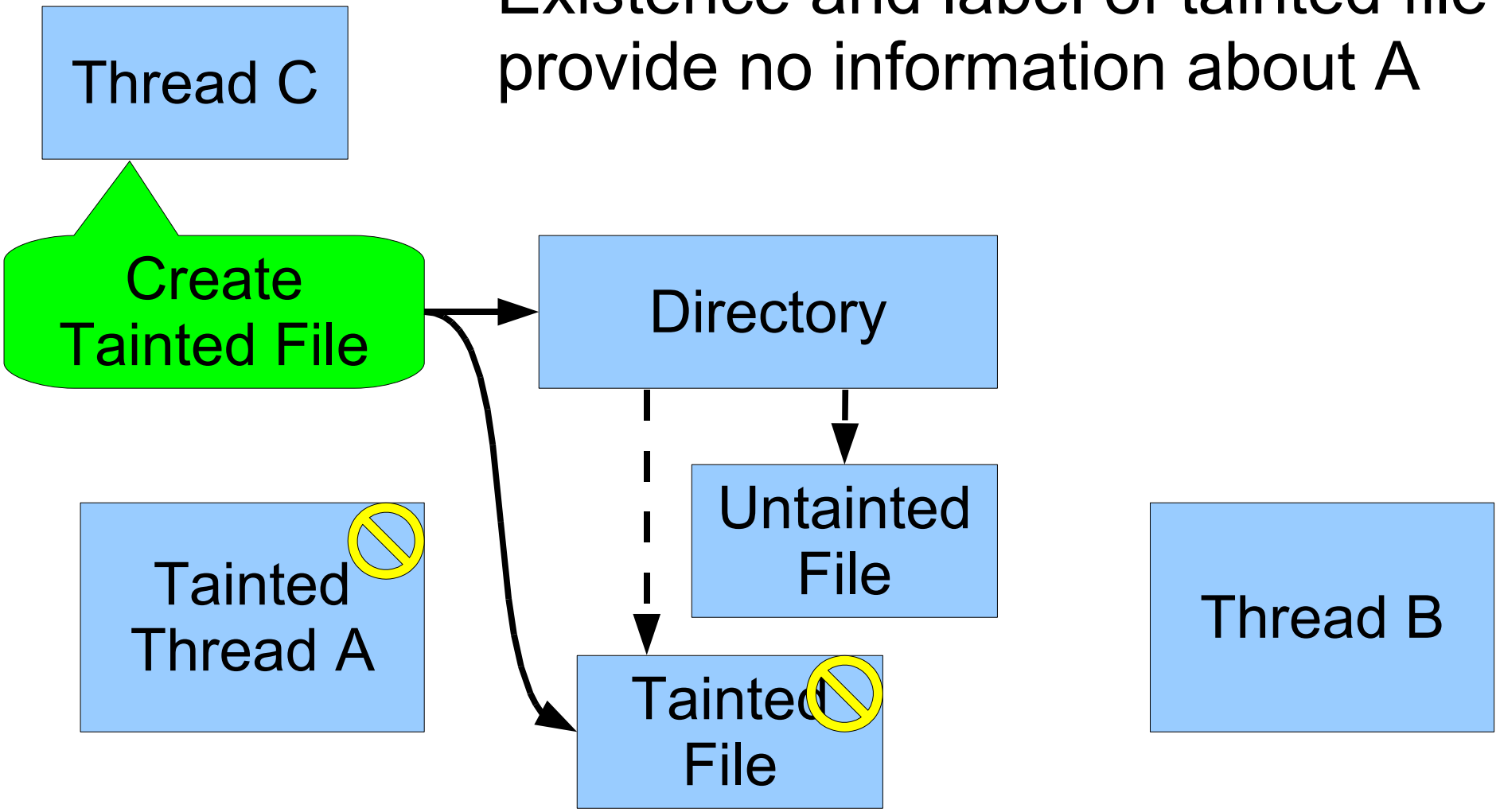
Who creates tainted files?

- Tainted thread can't modify untainted directory to place the new file there...



HiStar: Untainted thread pre-creates tainted file

- Existence and label of tainted file provide no information about A



Reading a tainted file

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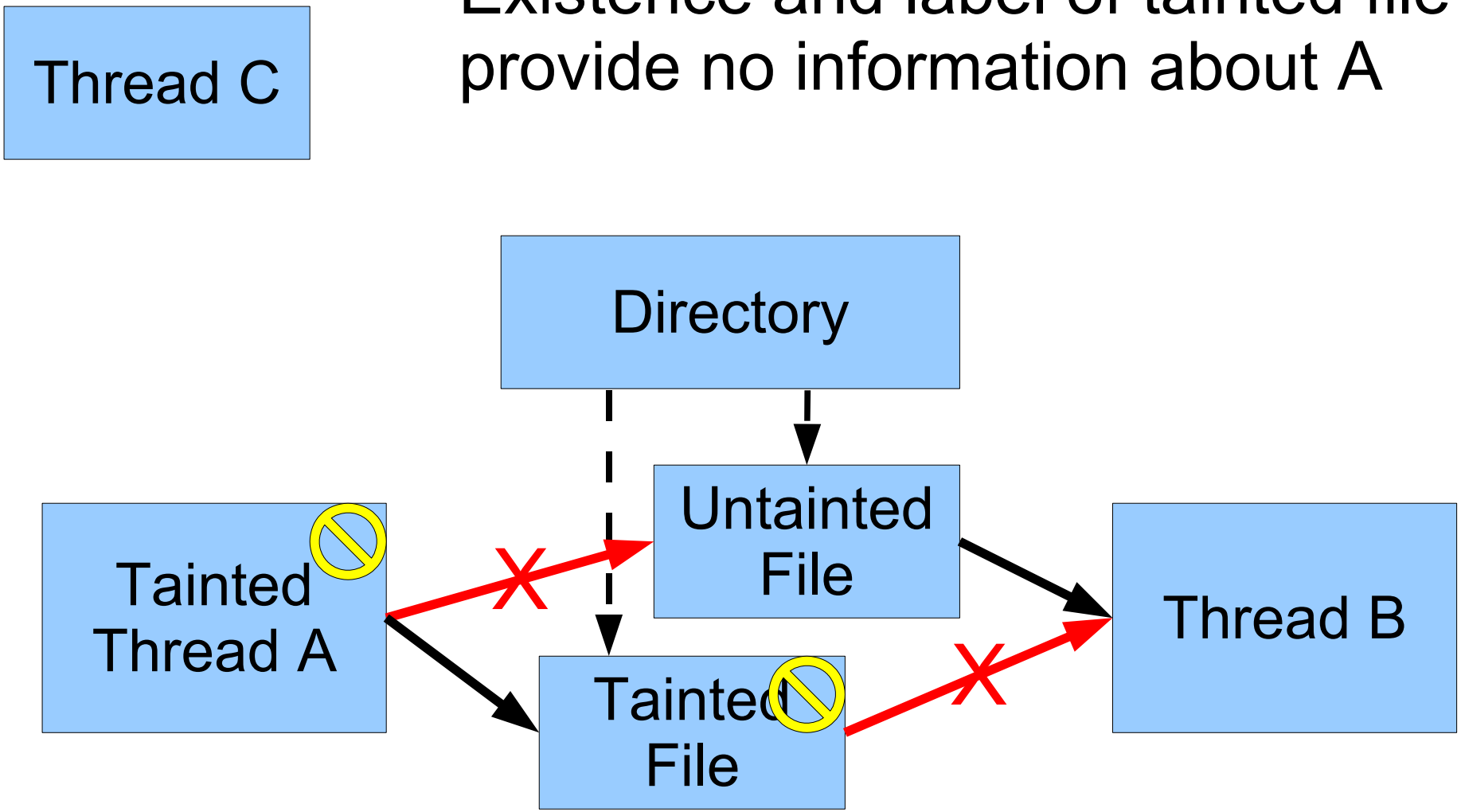

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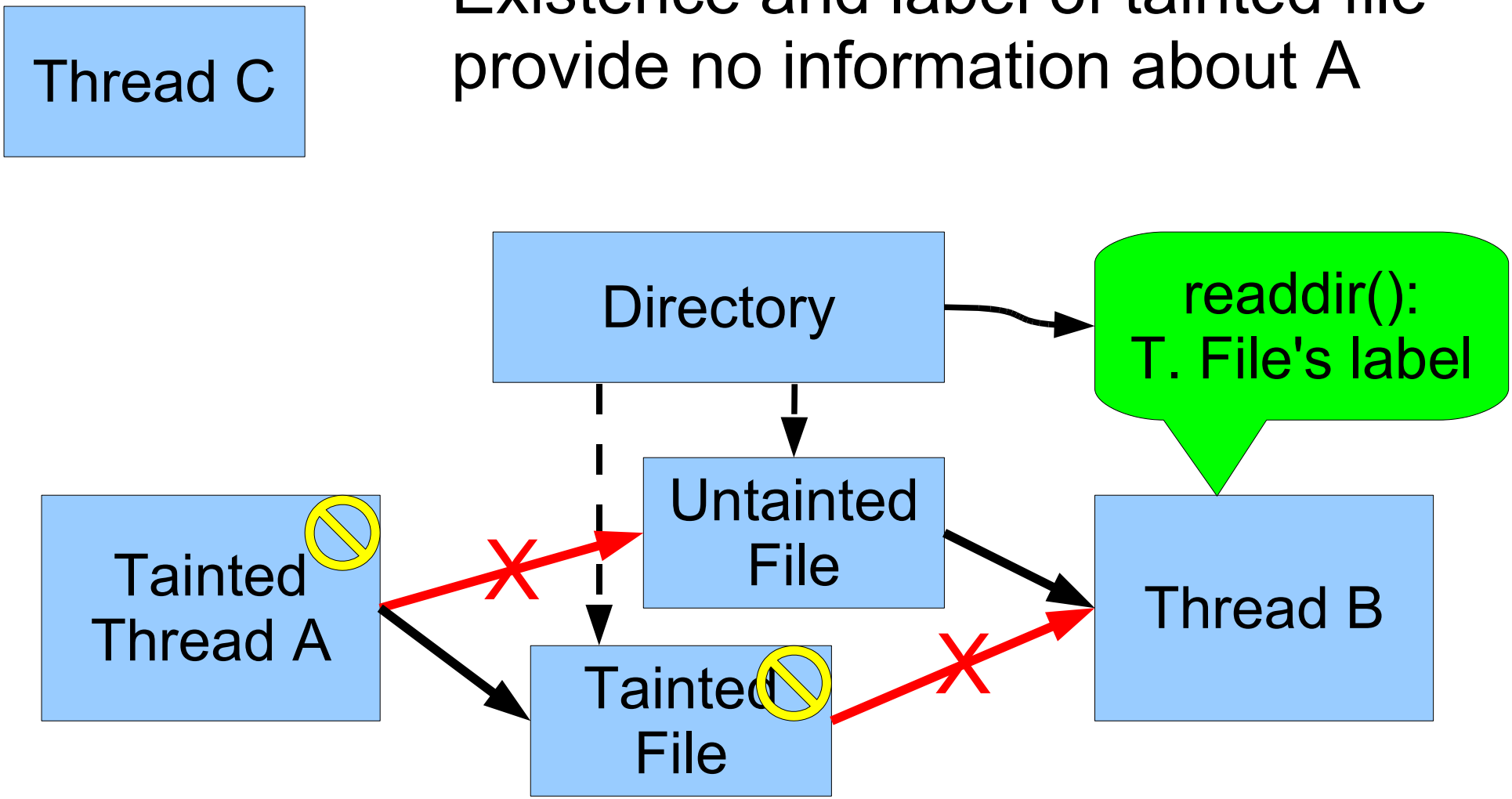
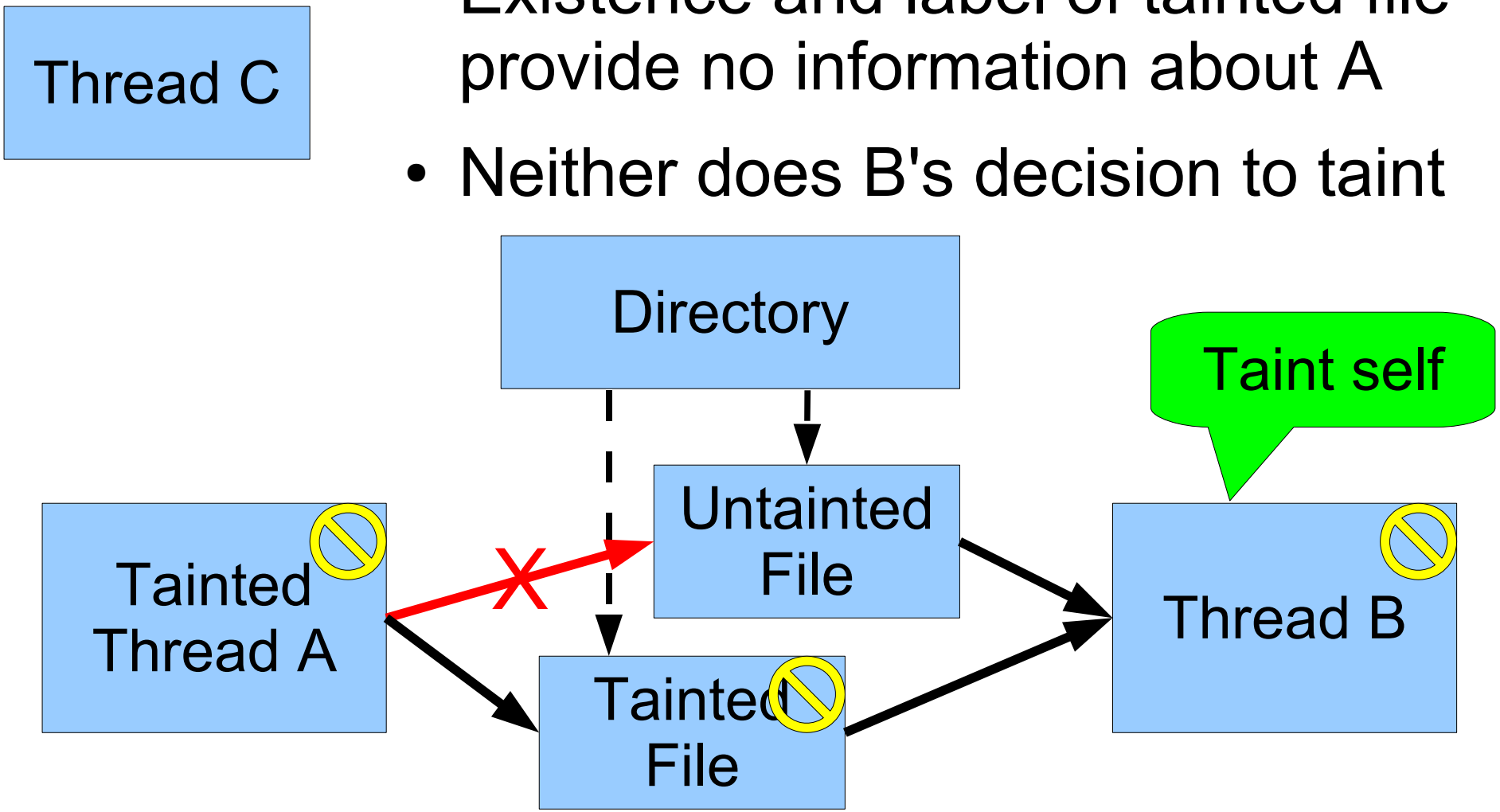


Reading a tainted file

- Existence and label of tainted file provide no information about A
- Neither does B's decision to taint

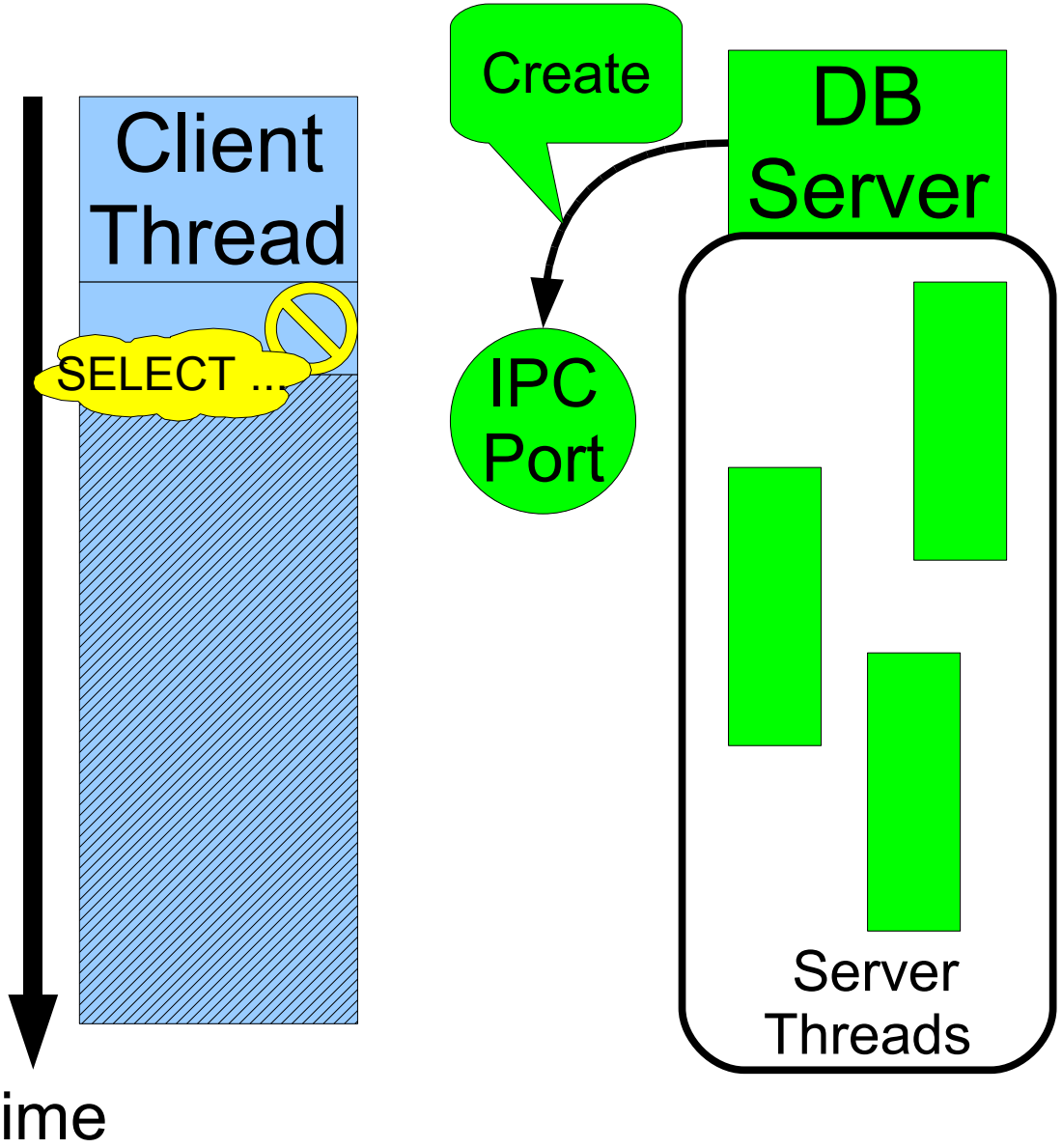


HiStar avoids file covert channels

- Immutable labels prevent covert channels that communicate through label state
- Untainted threads pre-allocate tainted files
  - File existence or label provides no secret information
- Threads taint themselves to read tainted files
  - Tainted file's label accessible via parent directory

Problems with IPC

- IPC with tainted client
  - Taint server thread during request



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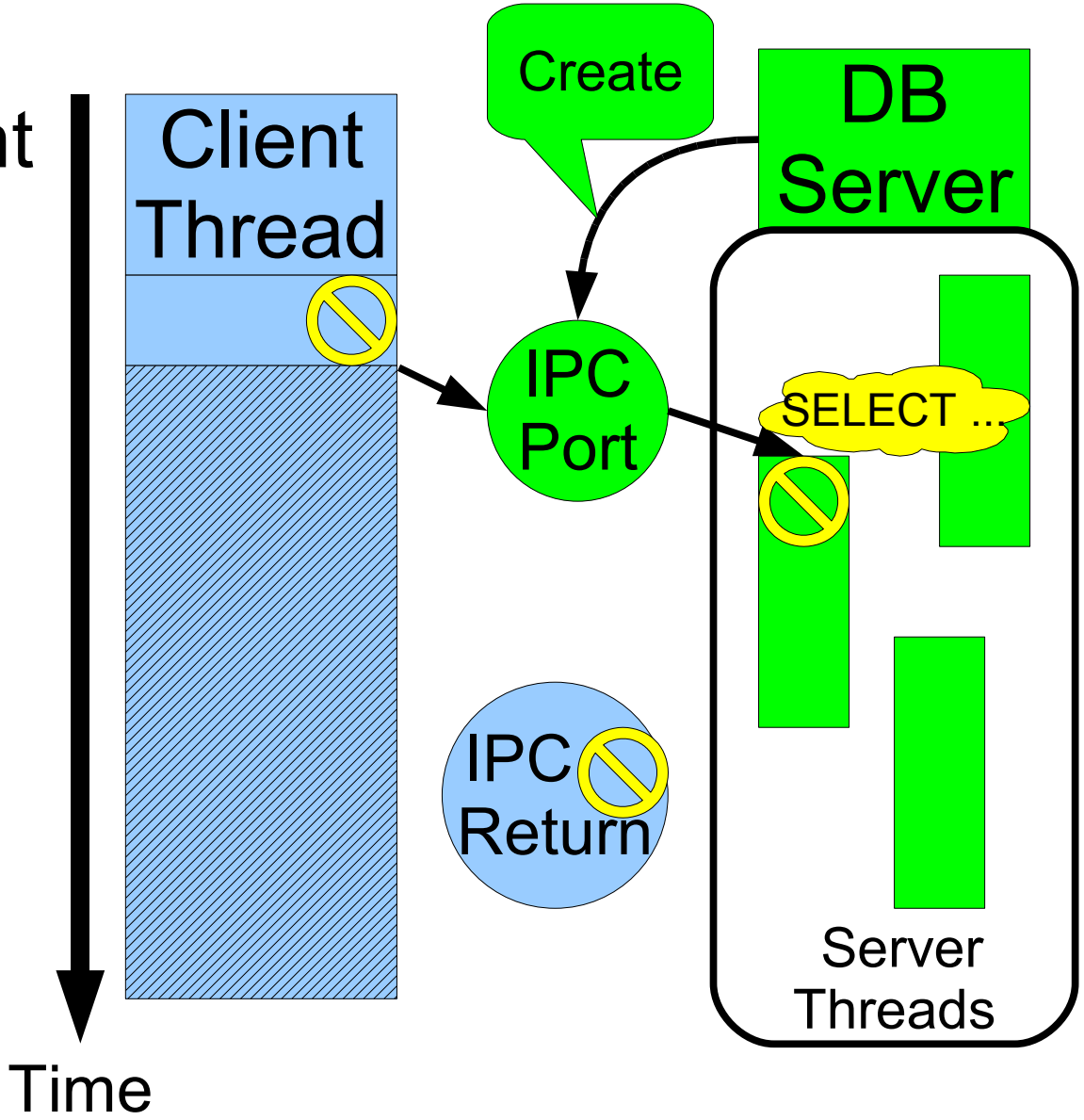

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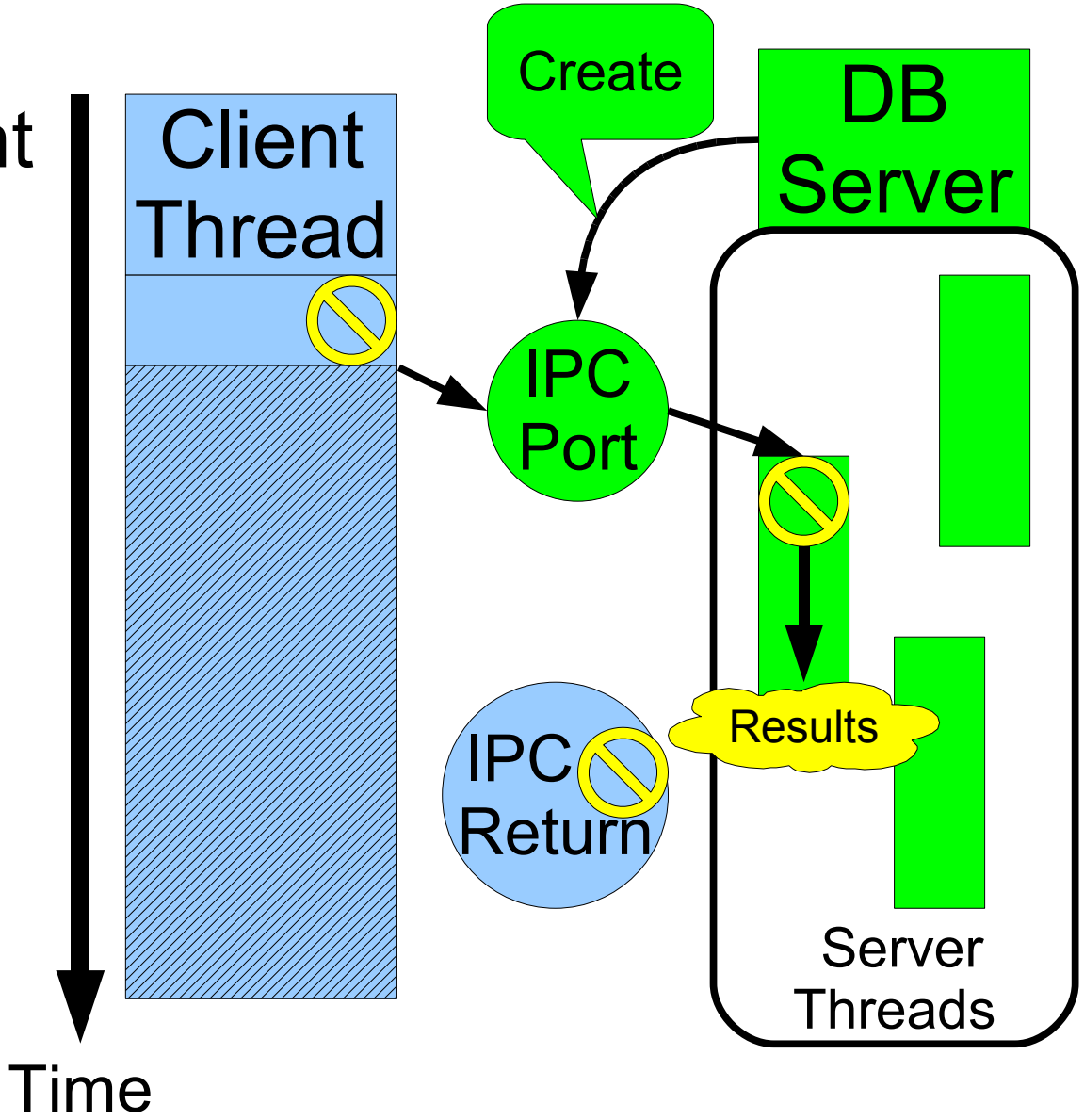

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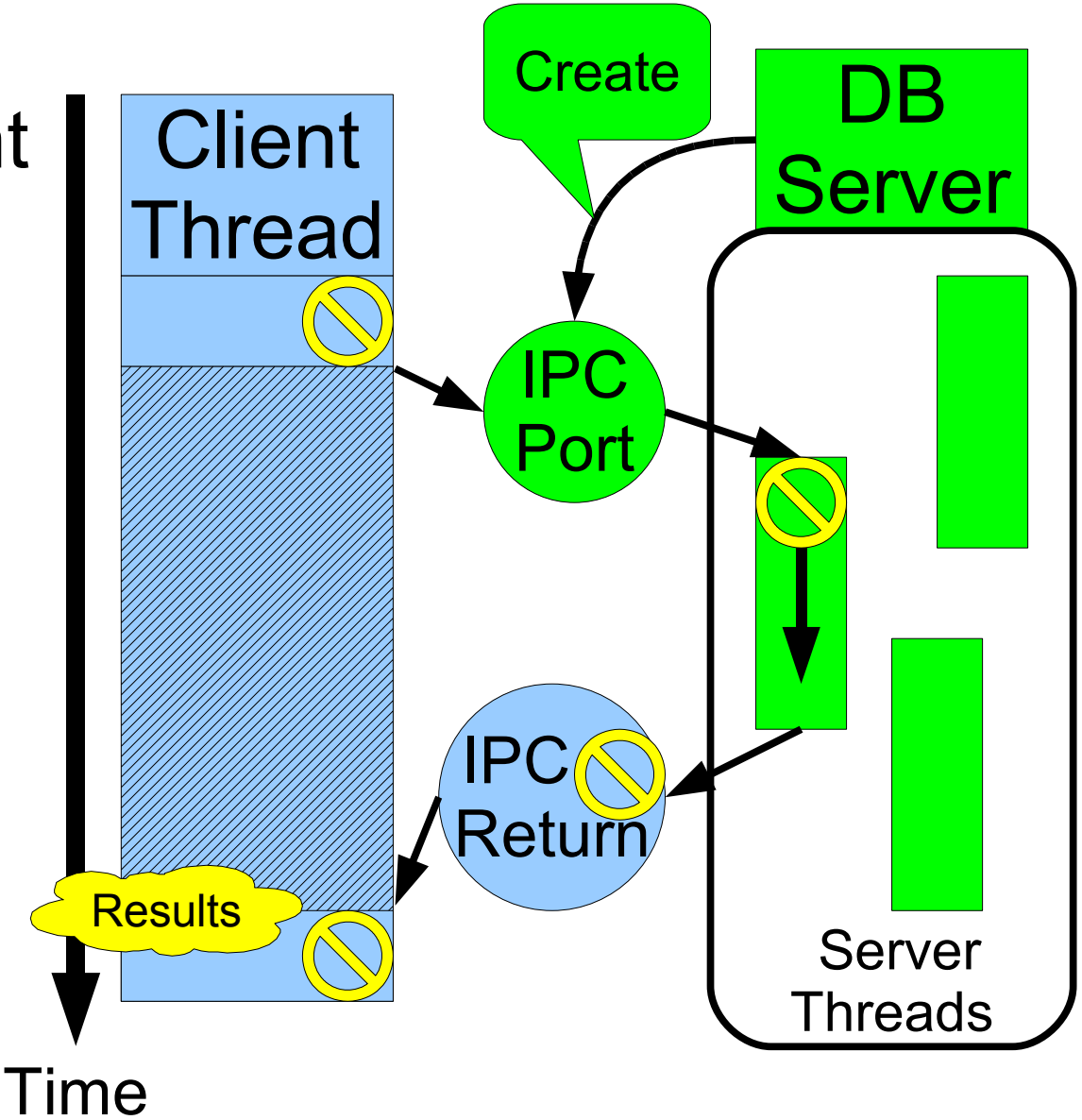
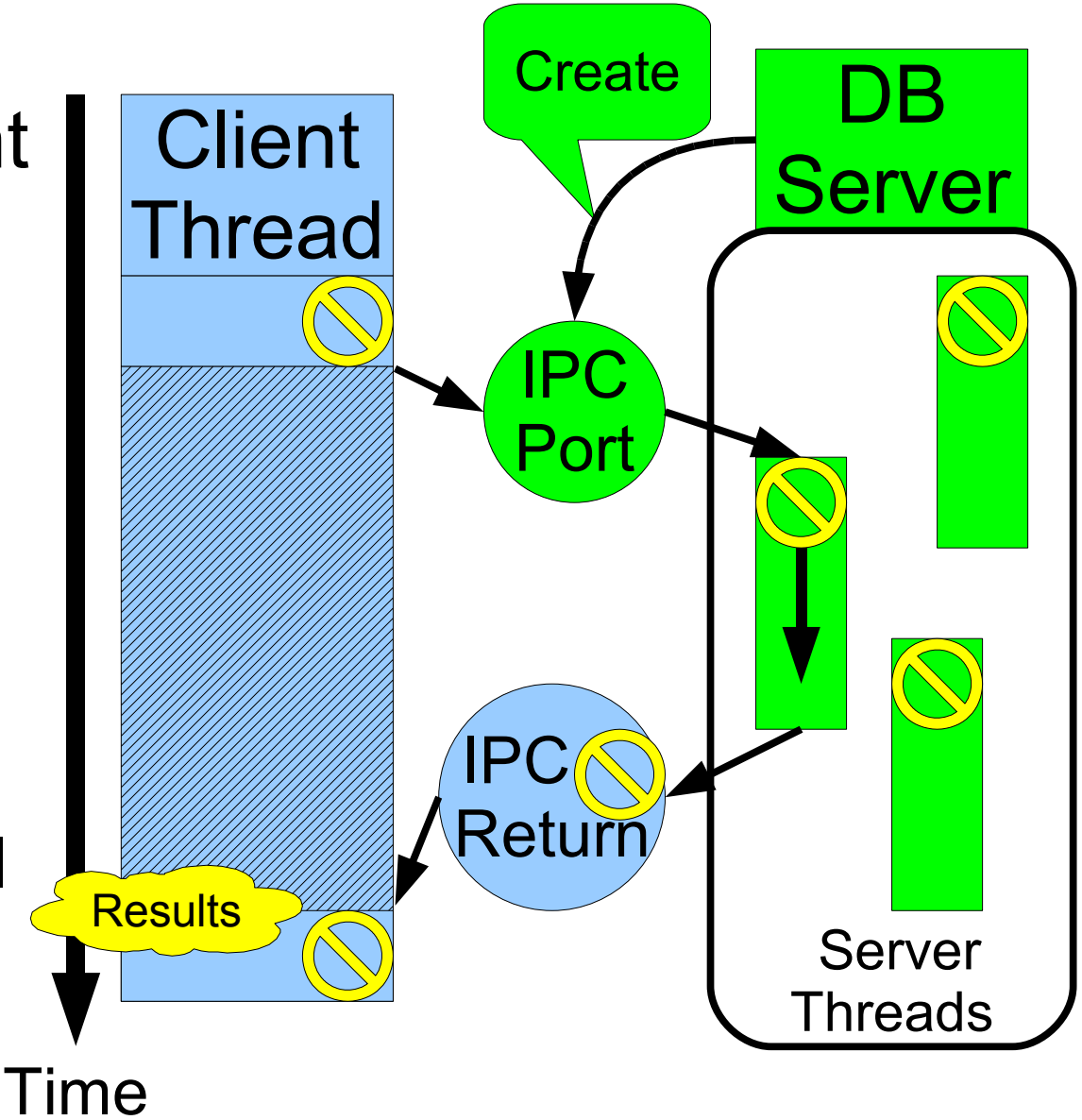


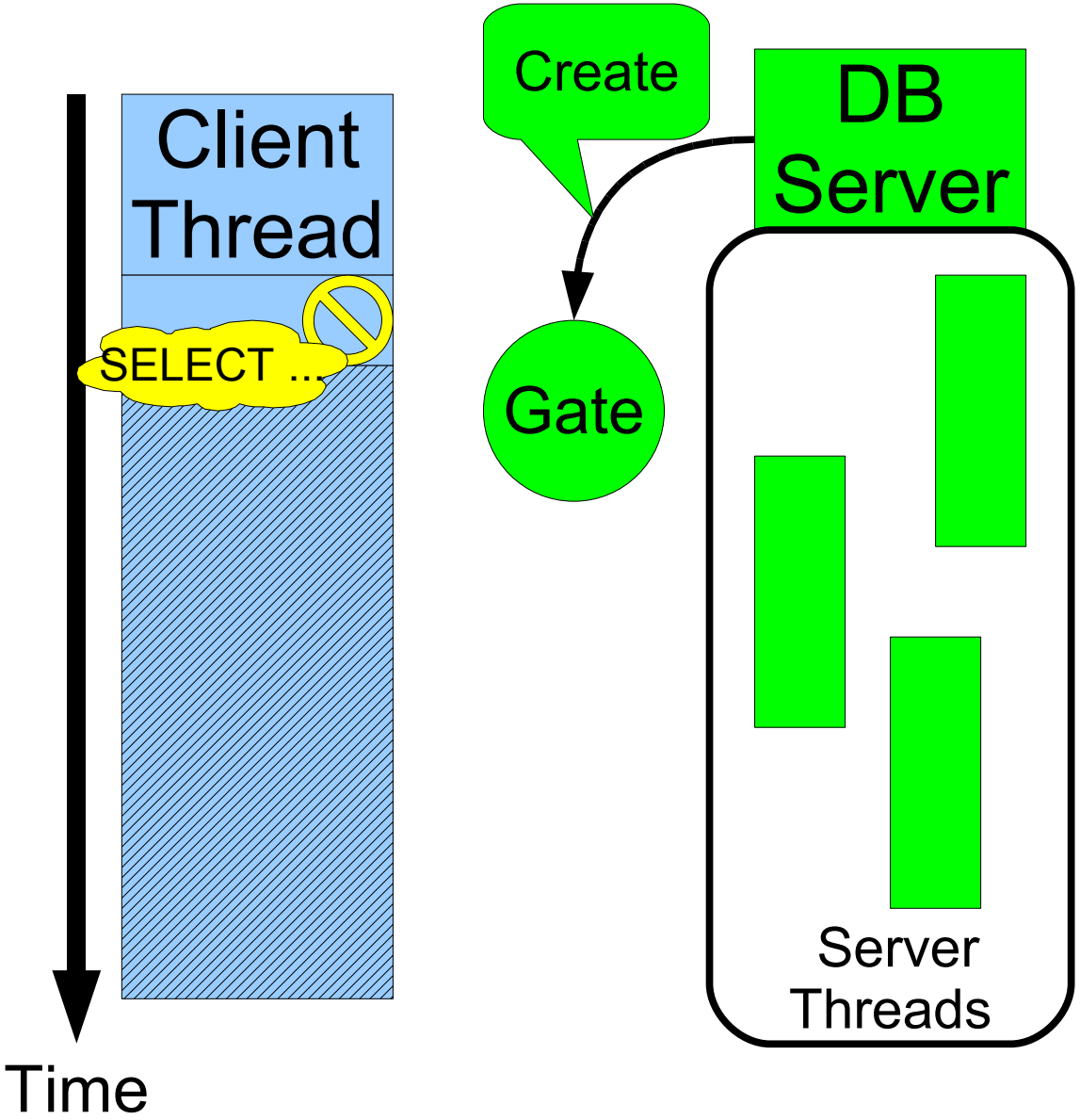
Problems with IPC

- IPC with tainted client
  - Taint server thread during request
  - Secrecy preserved?
- Lots of client calls
  - Limit server threads? Leaks information...
  - Otherwise, no control over resources!



Gates make resources explicit

- Client donates initial resources (thread)



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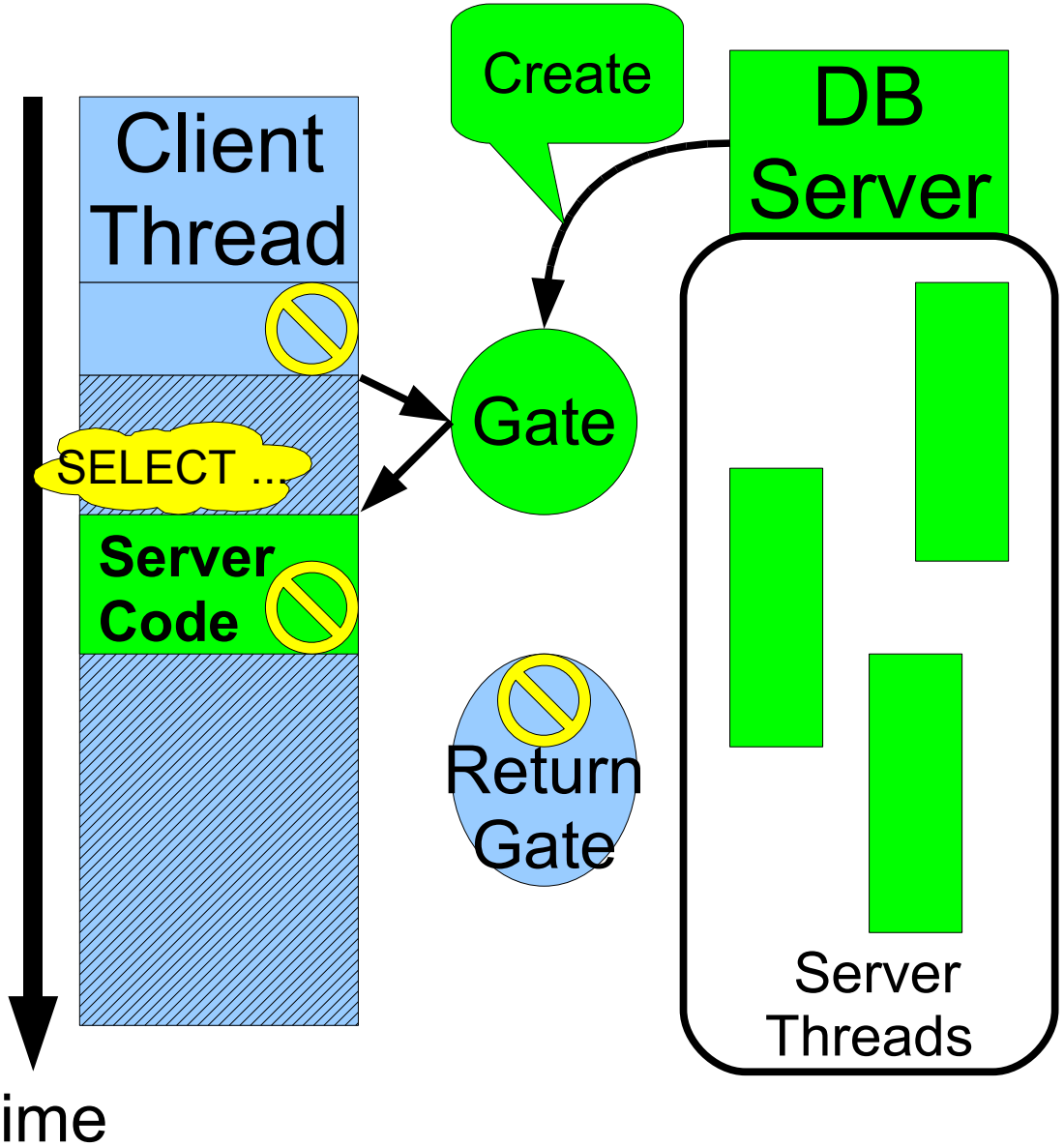

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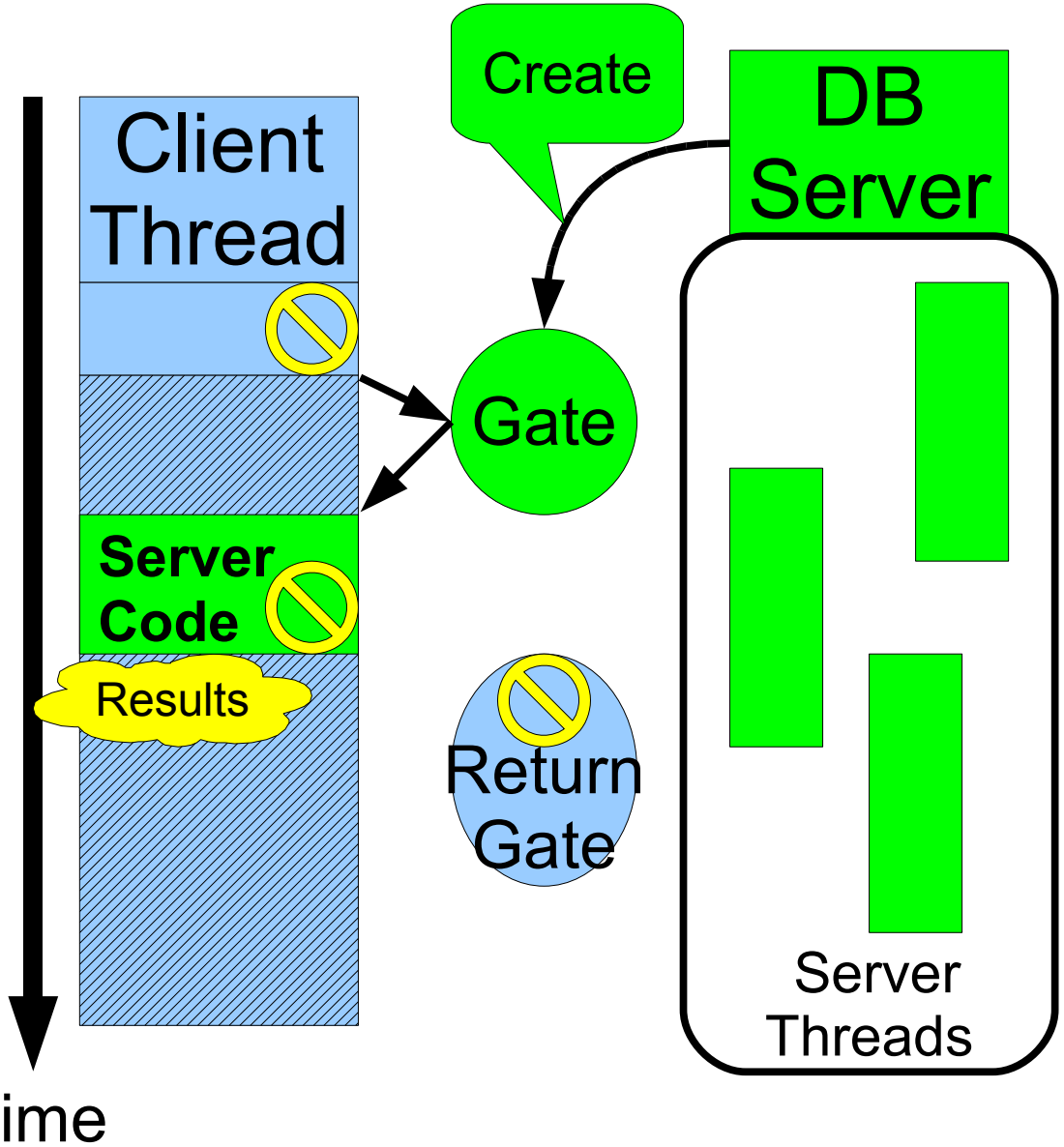

Gates make resources explicit

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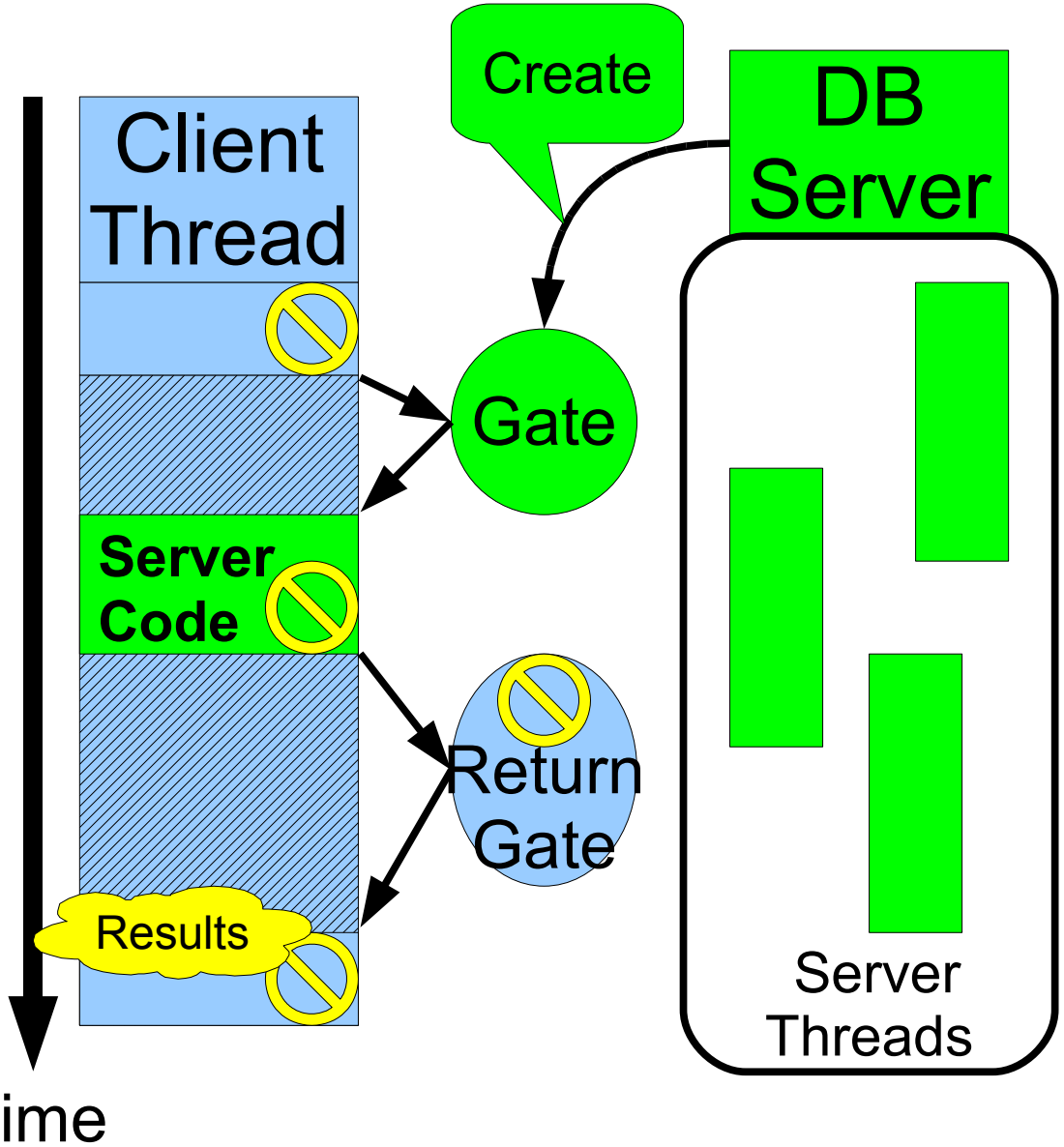
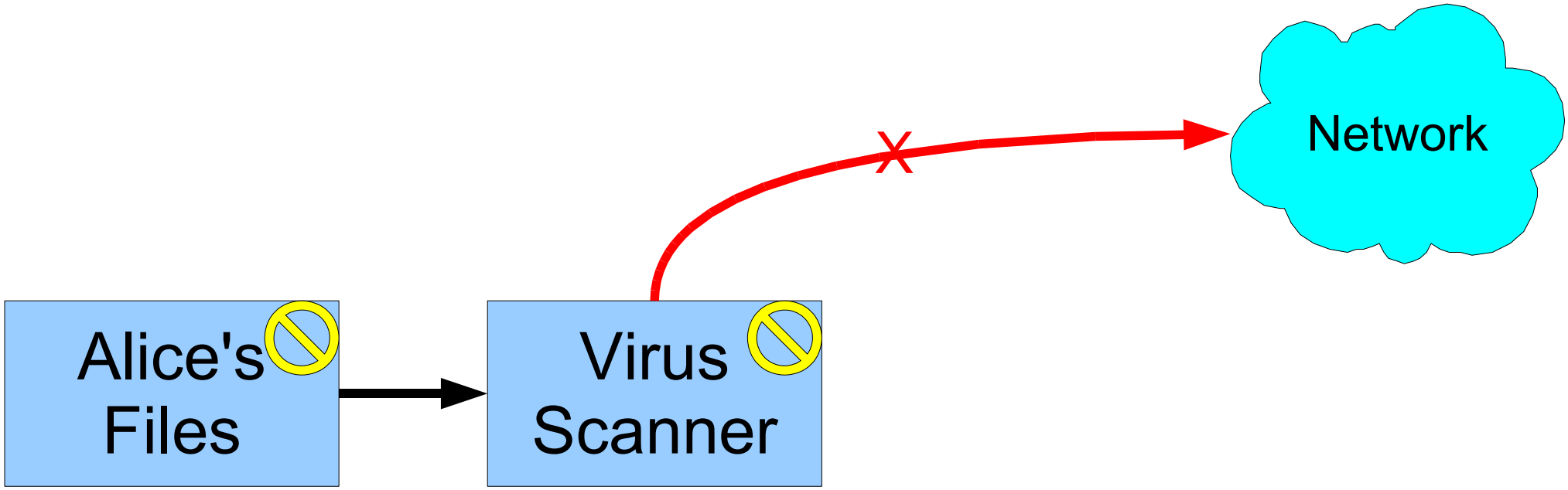
- Client thread runs in server address space, executing server code
- No implicit resource allocation – no leaks

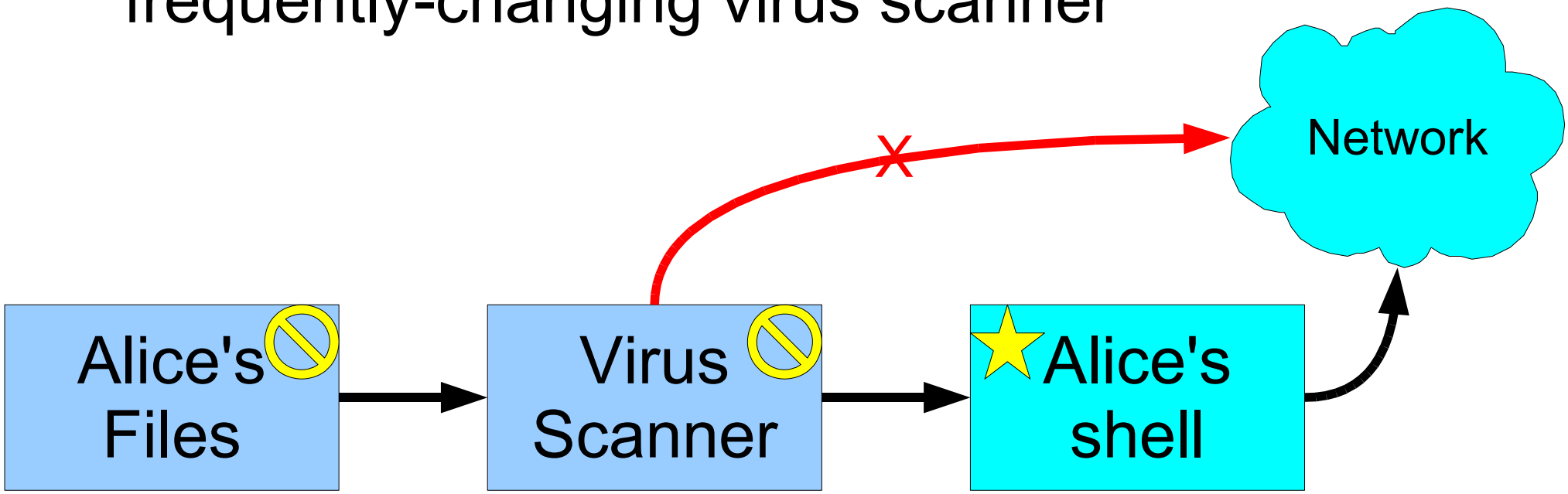


How do we get anything out?

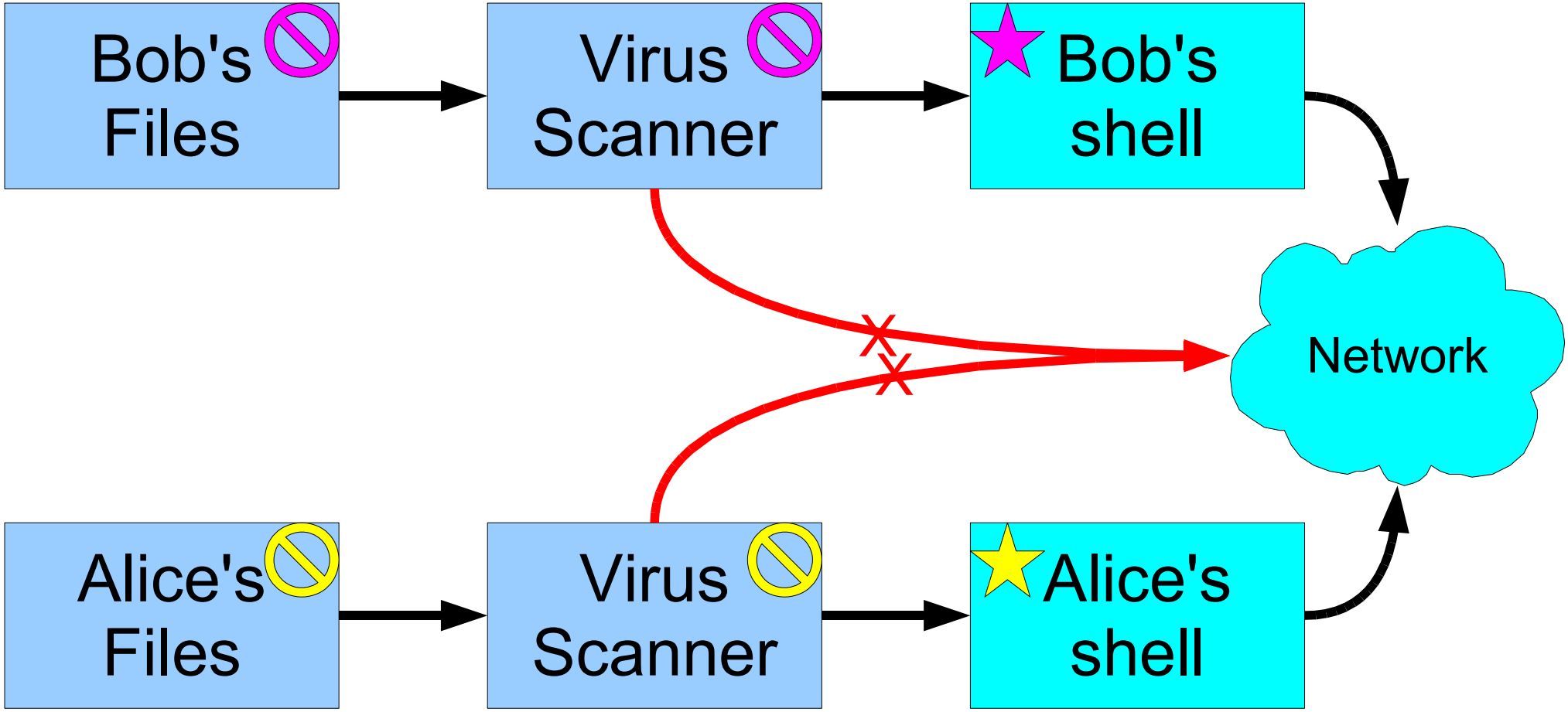


“Owner” privilege

- Star can get around information flow restrictions
- Small, trusted shell can isolate a large, frequently-changing virus scanner



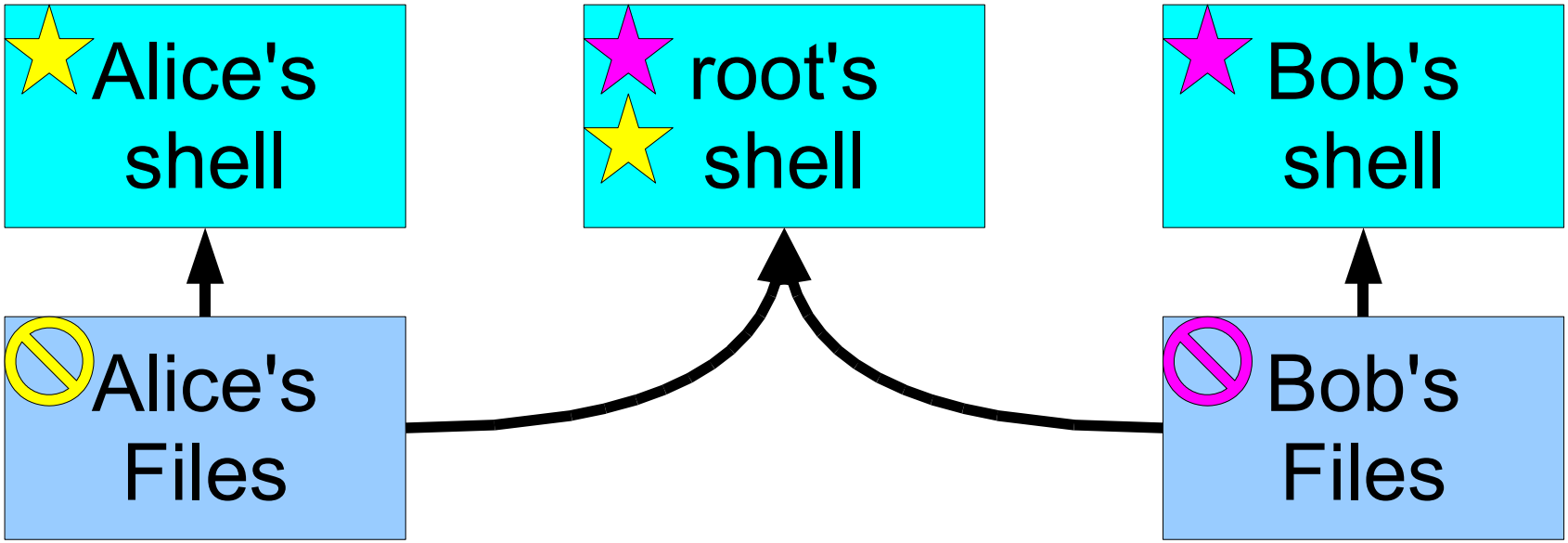
Multiple categories of taint



- Owner privilege and information flow control are the only access control mechanism
- Anyone can allocate a new category, gets star

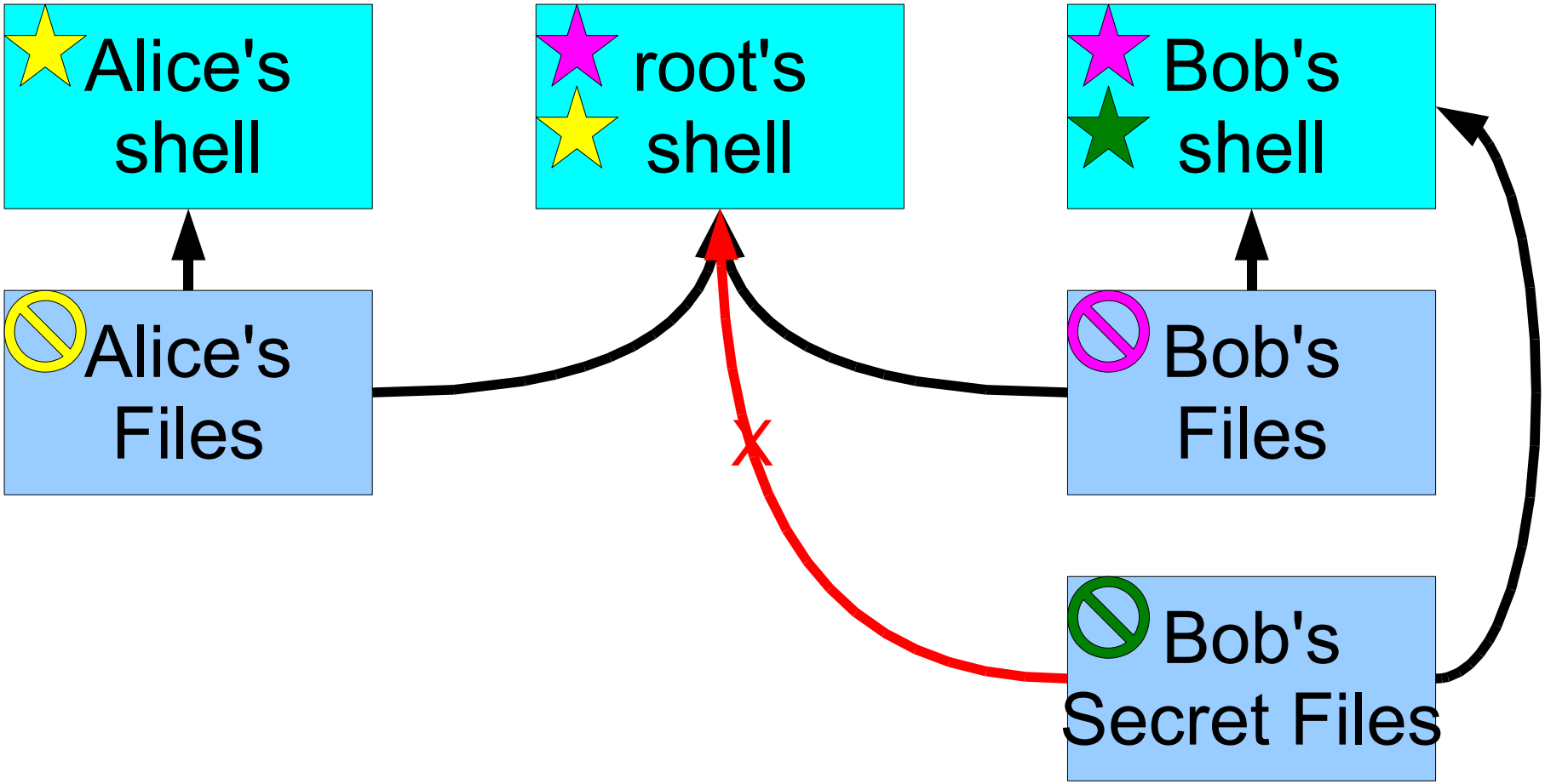
HiStar root privileges are explicit

- Kernel gives no special treatment to root



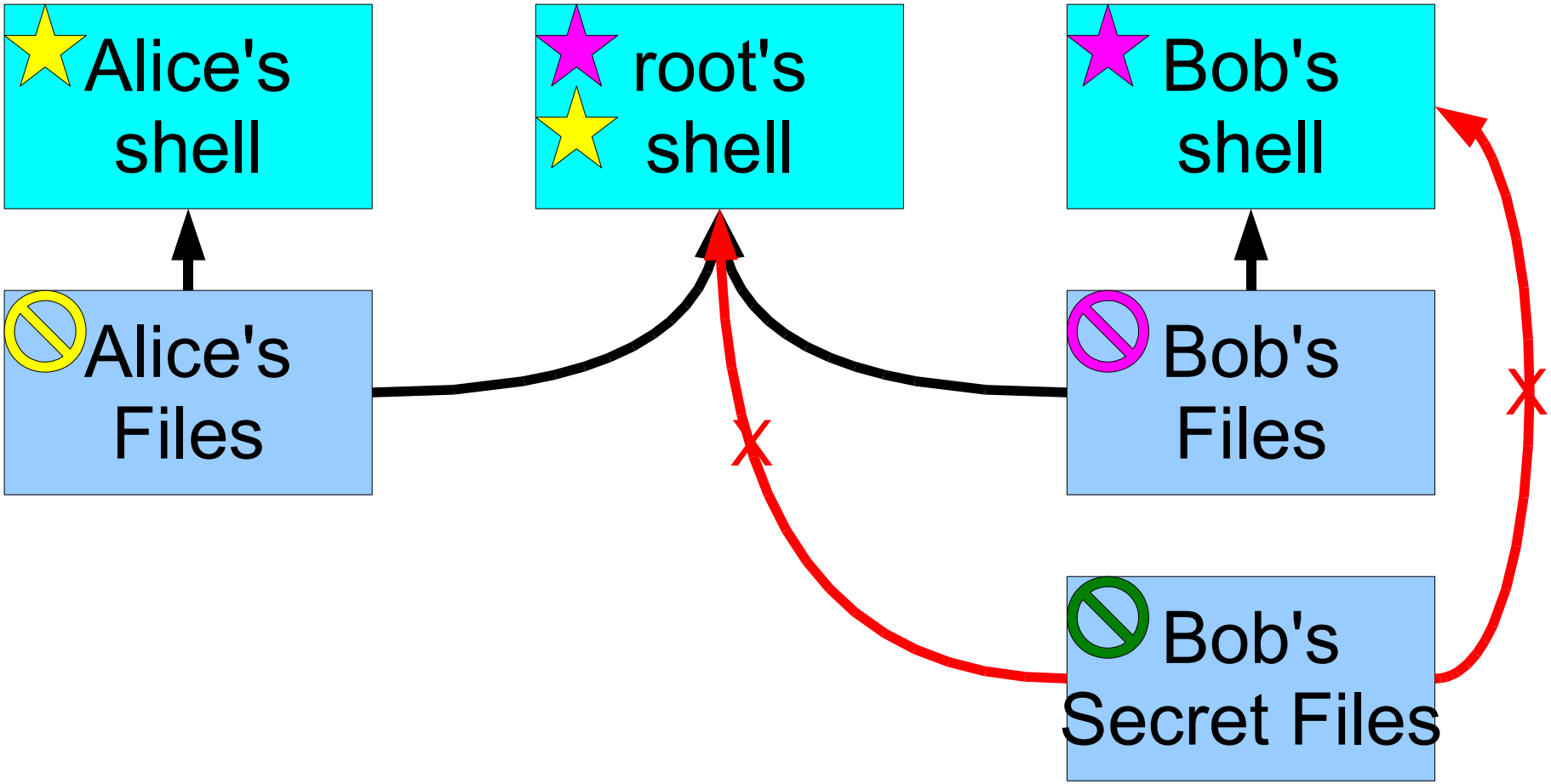
HiStar root privileges are explicit

- Users can keep secret data inaccessible to root

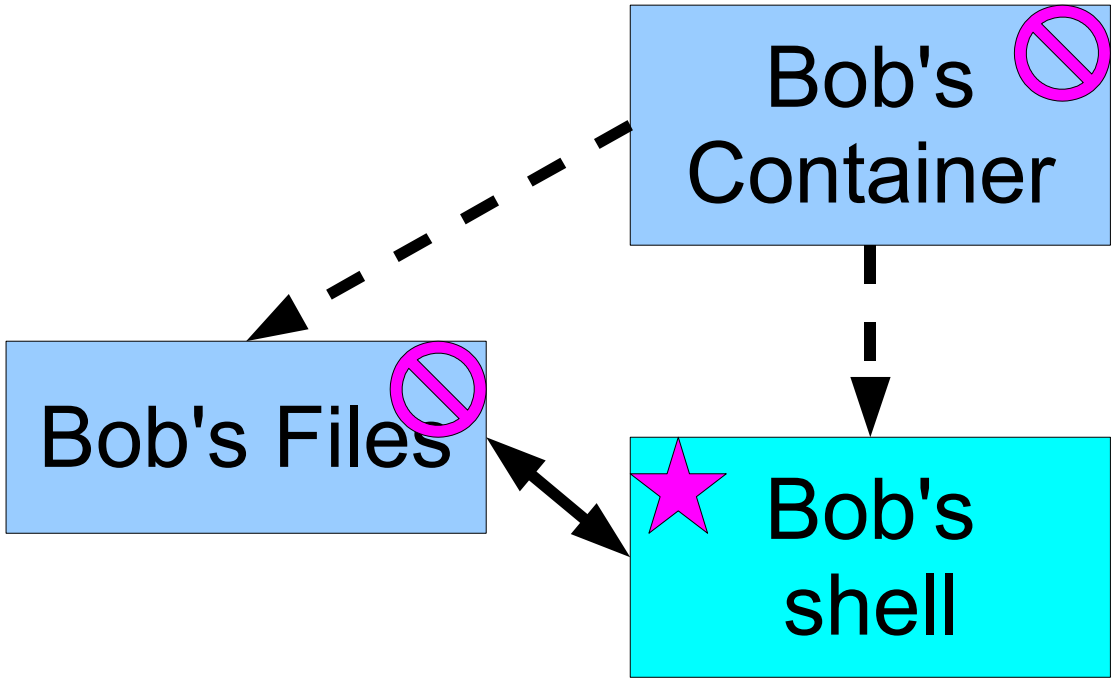


What to do with inaccessible files?

- Noone has privilege to access Bob's Secret Files

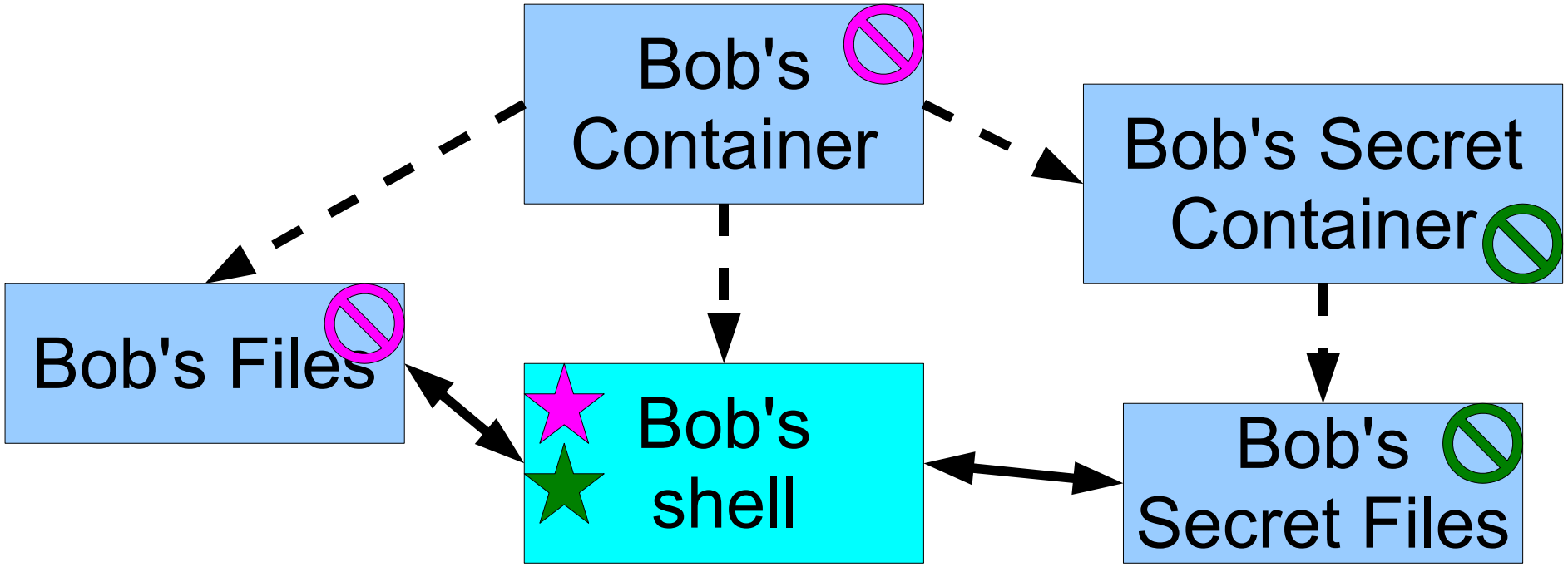


HiStar resource allocation



HiStar resource allocation

- Create a new sub-container for secret files



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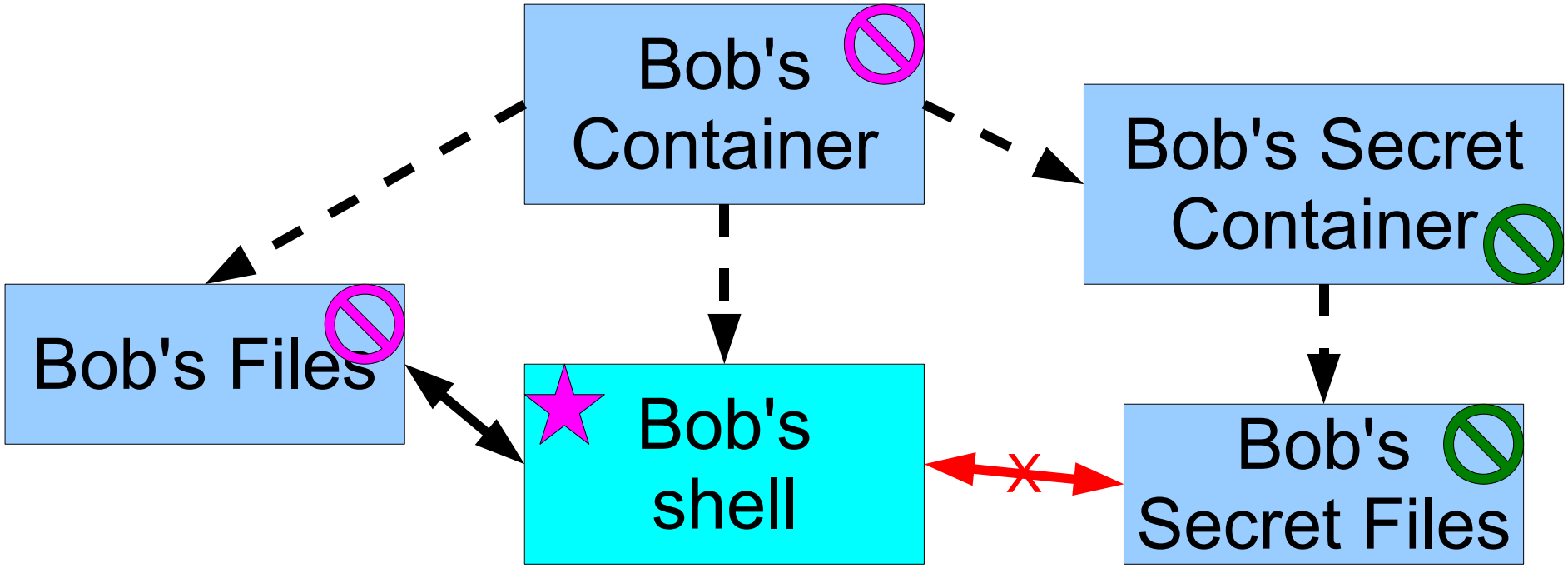
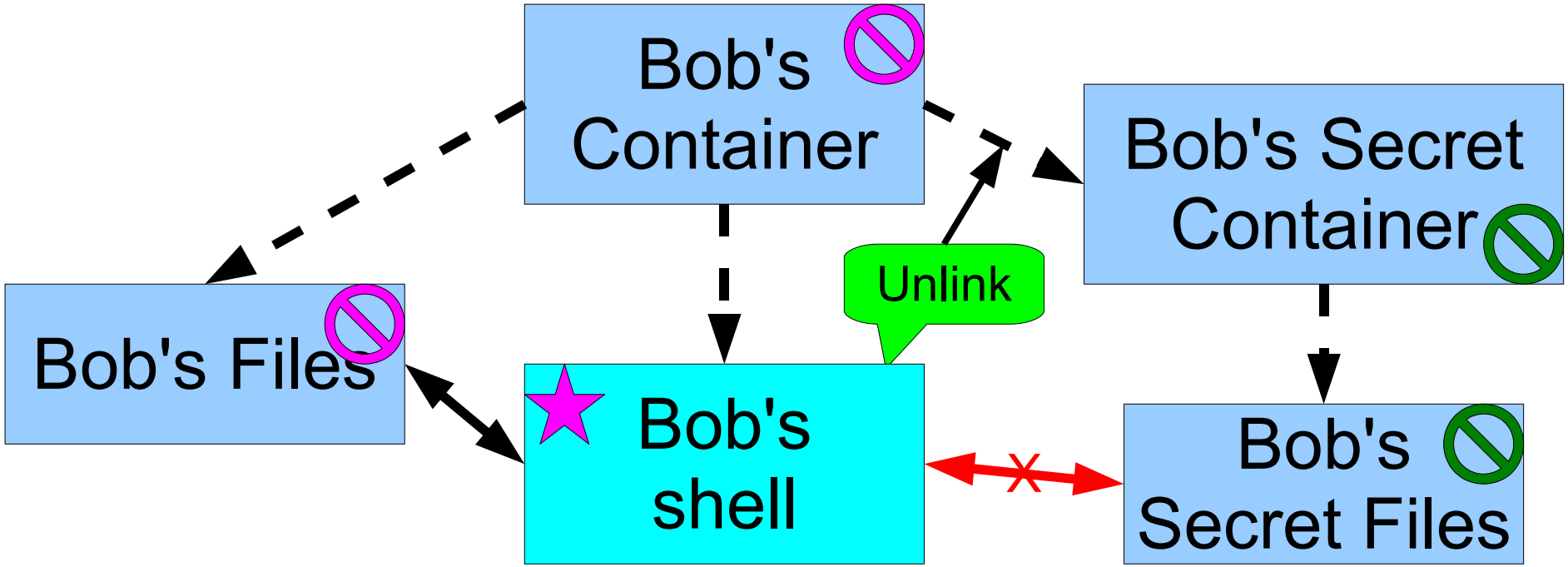


HiStar resource allocation

- Create a new sub-container for secret files
- Bob can delete sub-container even if he cannot otherwise access it!



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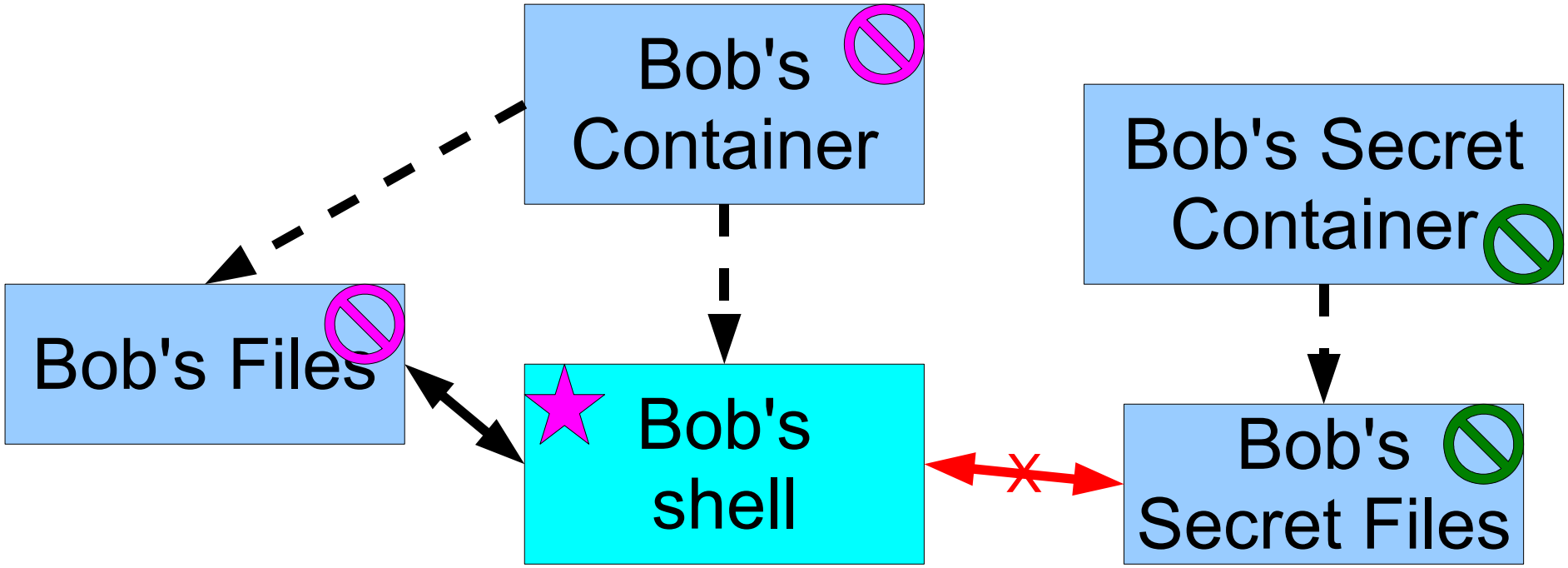

HiStar resource allocation

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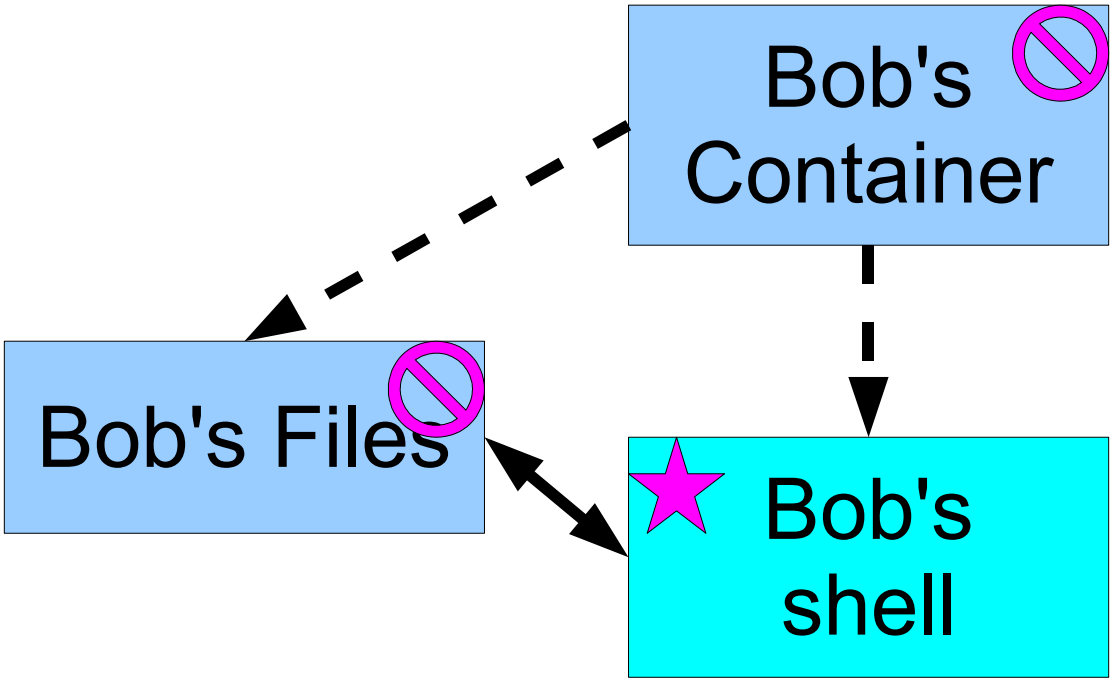
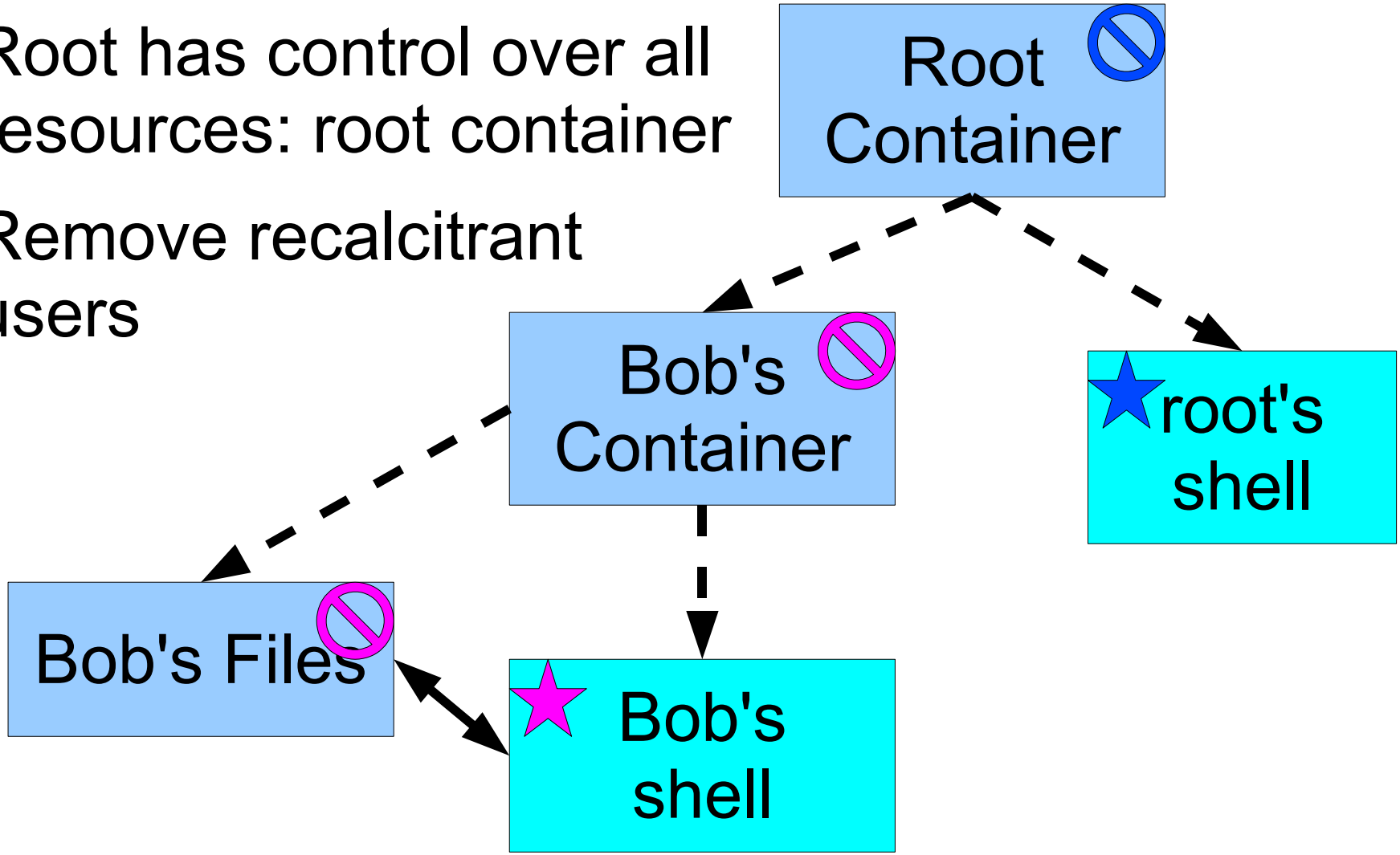


HiStar resource allocation

- Root has control over all resources: root container
- Remove recalcitrant users



Persistent Storage

- Unix: file system implemented in the kernel
  - Many potential pitfalls leading to covert channels: mtime, atime, link counts, ...
  - Would be great to implement it in user-space as well

- HiStar: Single-level store (like Multics / EROS)
  - All kernel objects stored on disk – memory is a cache
  - No difference between disk & memory objects
  - Eliminates need for trusted boot scripts

Single-level store

```
% ssh root@histar
HiStar#
```

Single-level store

```
% ssh root@histar
HiStar# reboot
```

Single-level store

```
% ssh root@histar
HiStar# reboot
rebooting...
```

Kernel checkpoints to disk:
- Threads
- Address spaces
- Segments (memory)
- ...

and then reboots machine

Single-level store

```
% ssh root@histar
HiStar# reboot
rebooting...
done
HiStar#
```

Kernel checkpoints to disk:
- Threads
- Address spaces
- Segments (memory)
- ...

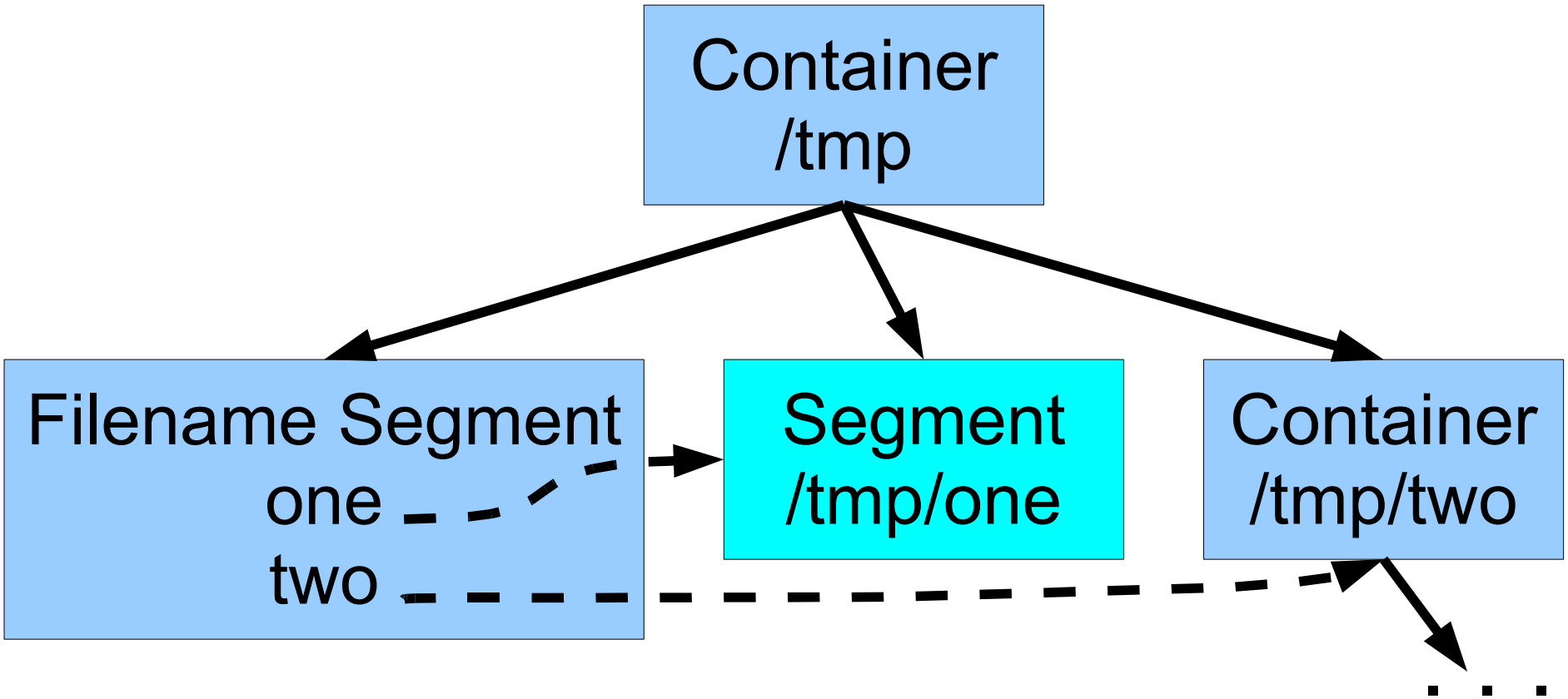
and then reboots machine

Kernel boots up, reads in:
- Threads
- Address spaces
- Segments (memory)
- ...

and continues as before!

File System

- Implemented at user-level, using same objects
- Security checks separate from FS implementation



How to *really* reboot?

- Separate command called "`ureboot`"

- Kills all processes except itself (`ureboot`)
  - Delete all containers, except for the file system
  - FS containers have special bit that excludes threads

- Starts a new `init` process
  - It will start everything else (TCP/IP stack, sshd, ...)

HiStar kernel design

- Kernel operations make information flow explicit
  - Explicit operation for thread to taint itself
    - Kernel never implicitly changes labels
  - Explicit resource allocation: gates, pre-created files
    - Kernel never implicitly allocates resources

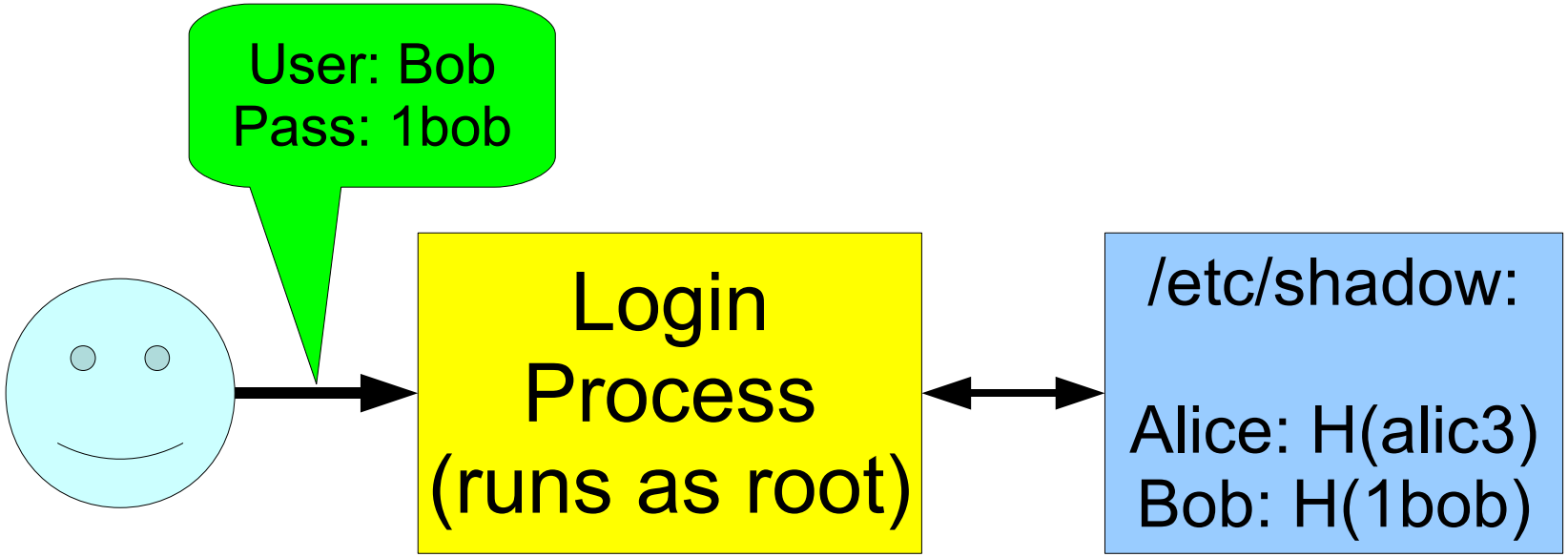
- Kernel has no concept of superuser
  - Users can explicitly grant their privileges to root
  - Root owns the top-level container

Applications

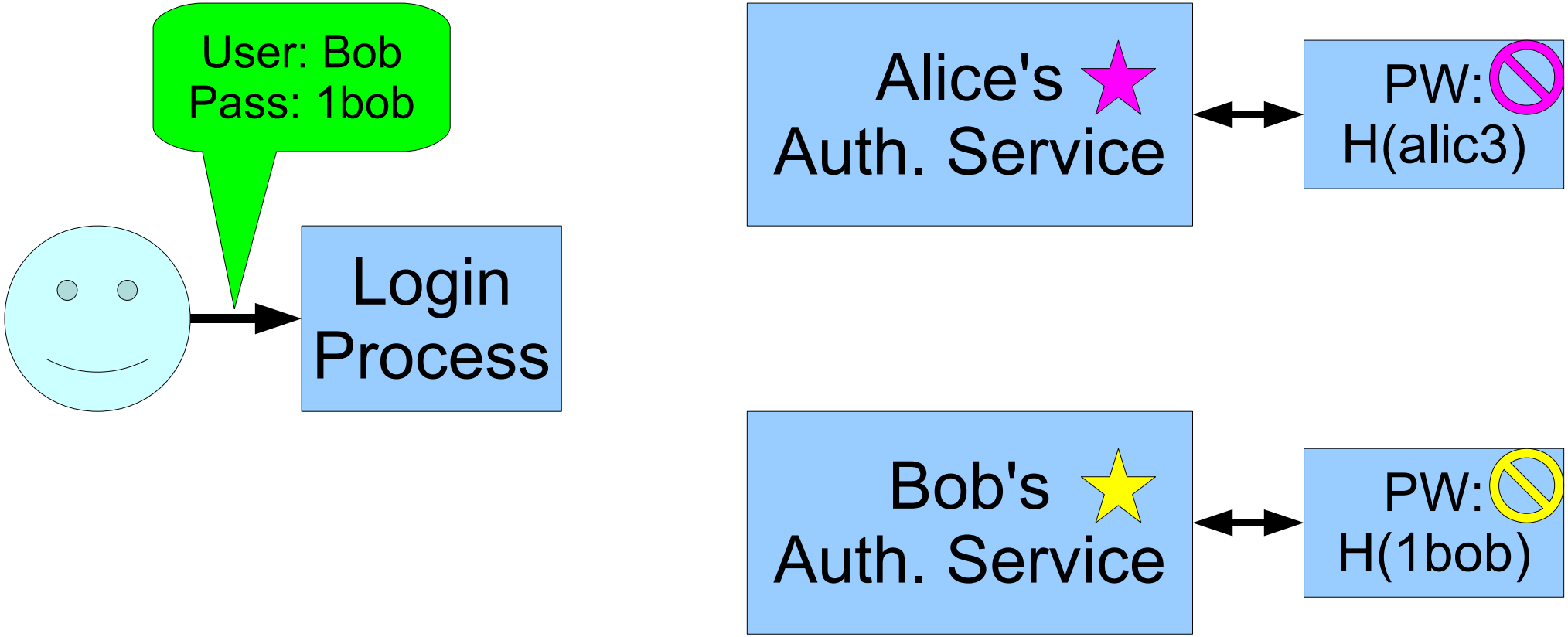
- Many Unix applications
  - gcc, gdb, openssh, ...
- High-security applications alongside with Unix
  - Untrusted virus scanners (already described)
  - VPN/Internet data separation (see paper)
  - login with user-supplied authentication code (next)
  - Privilege-separated web server

Login on Unix: highly centralized

- Difficult and error-prone to extend login process
  - Any bugs can lead to complete system compromise!

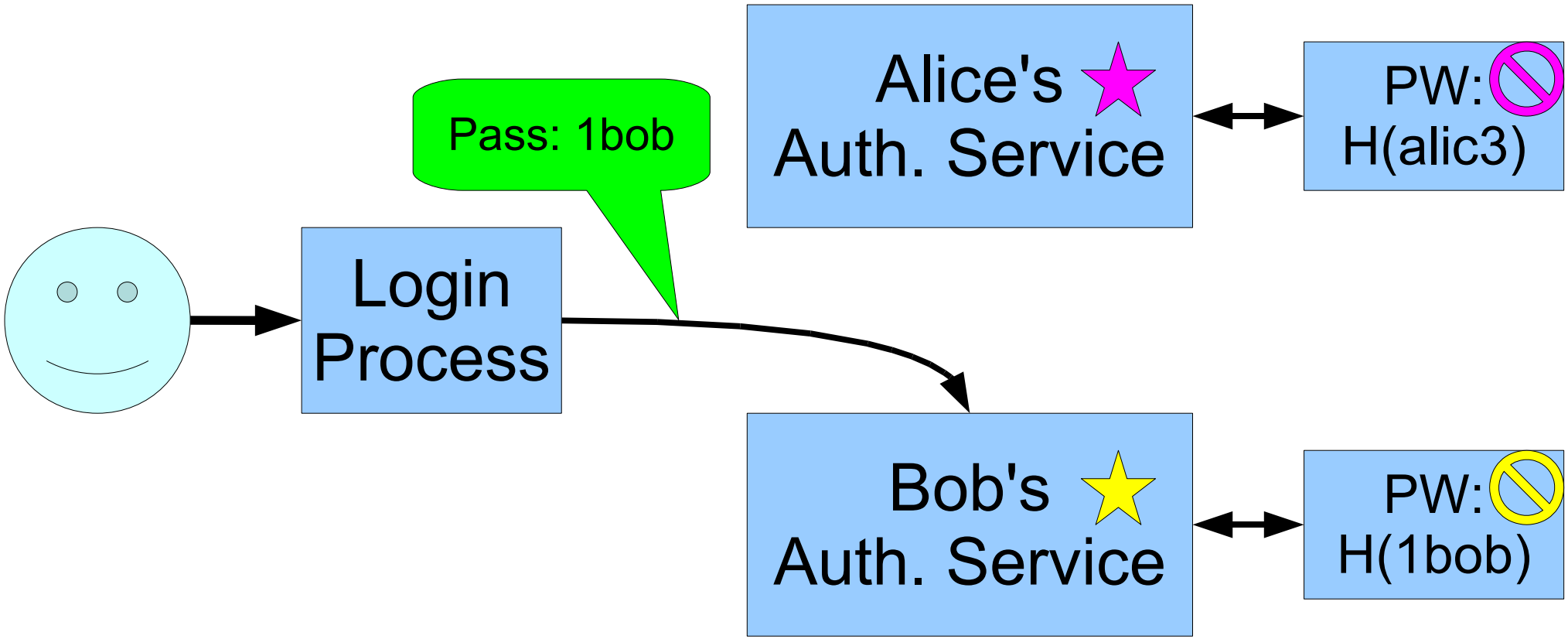


Login on HiStar: less trusted code



- Login process requires no privileges
- Each user can provide their own auth. service

Login on HiStar: less trusted code



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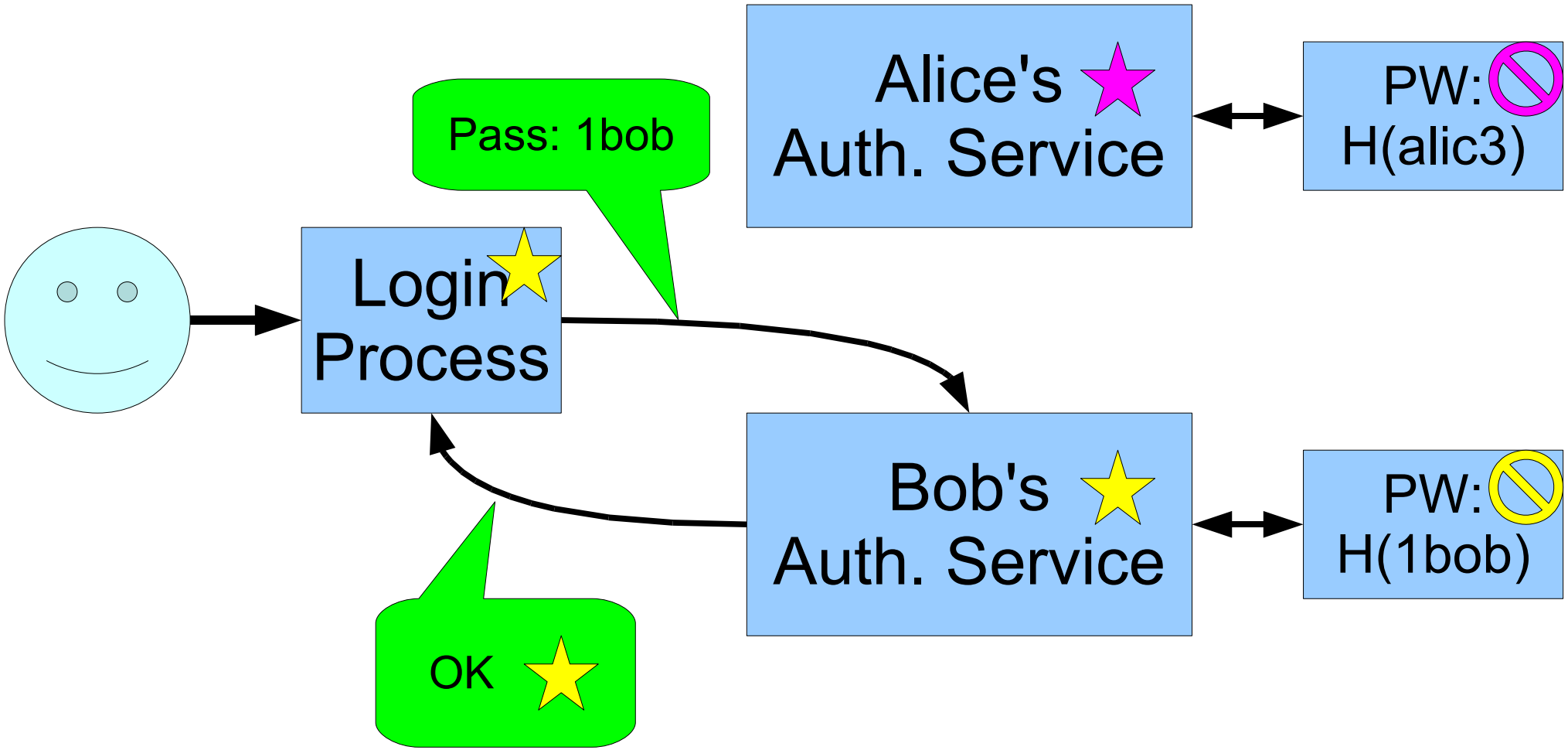
Login on HiStar: less trusted code

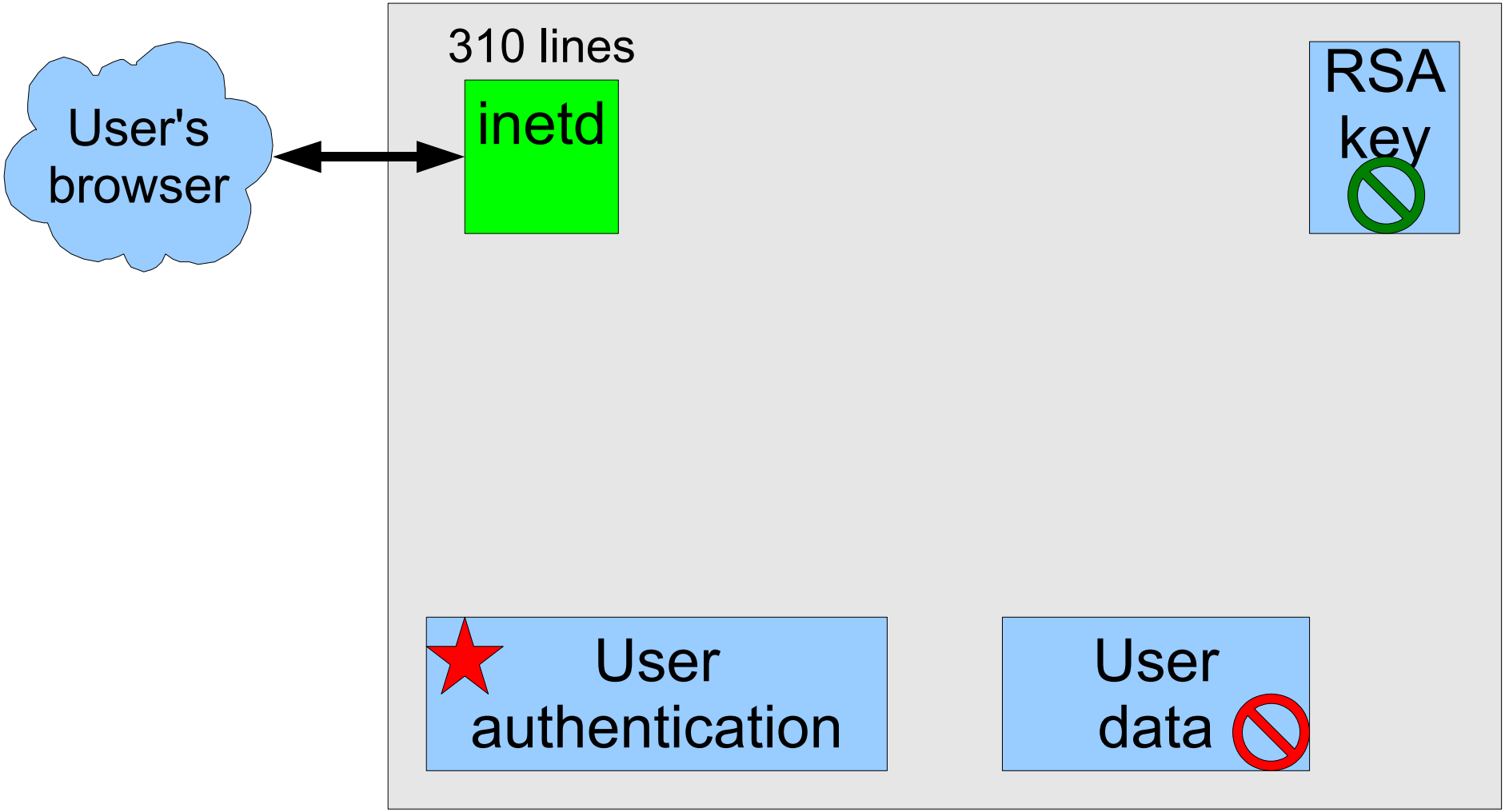


Login on HiStar: less trusted code

- No code runs with every user's privilege
  - Each user trusts their 300-line authentication agent
- Users supply their own authentication agent
  - Password checker, one-time passwords, ...
- OS ensures password is not disclosed
  - Even if user mistypes username and gives password to a malicious authentication agent (see paper)

HiStar SSL Web Server

- Only small fraction of code (green) is trusted



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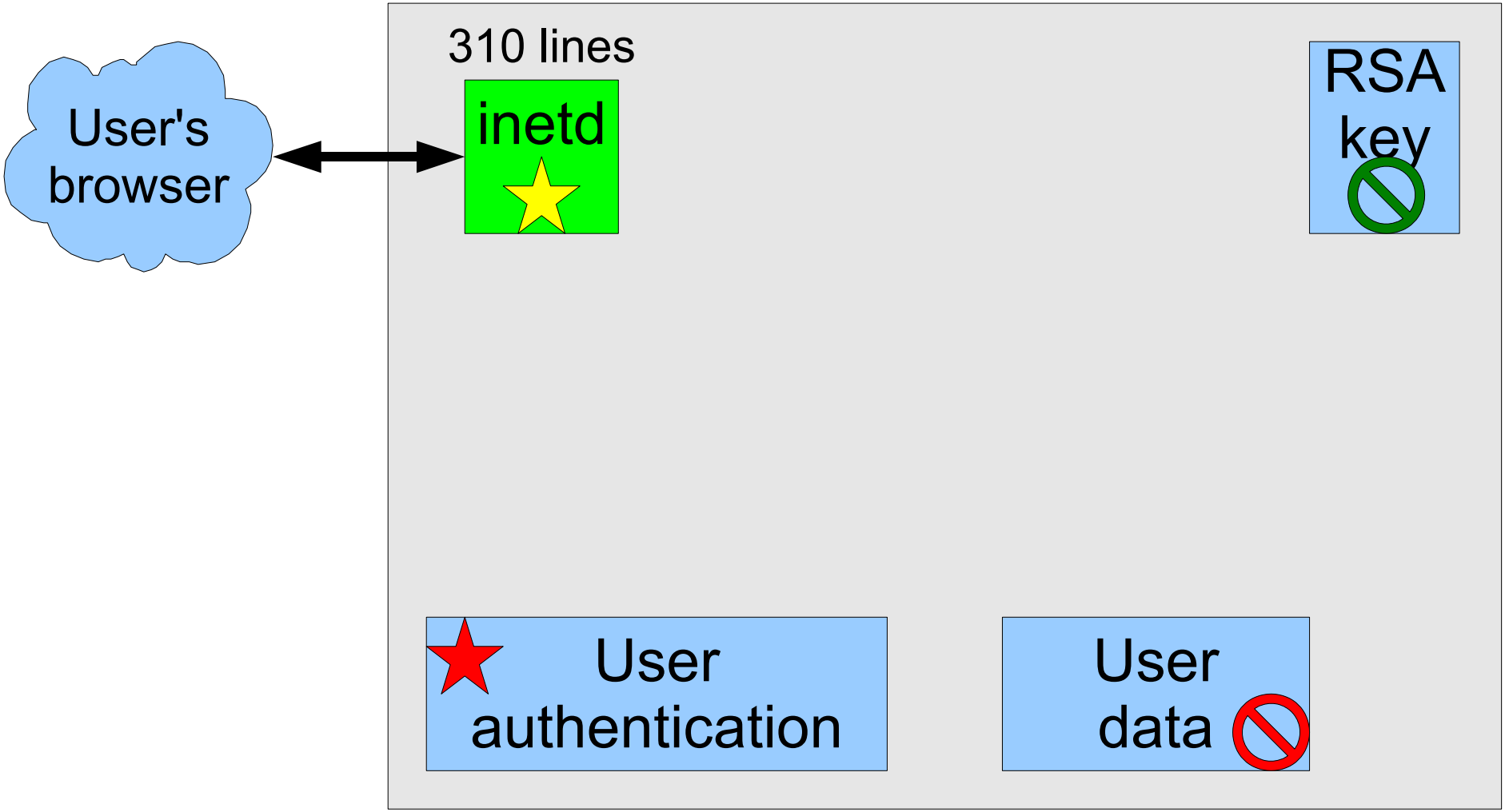
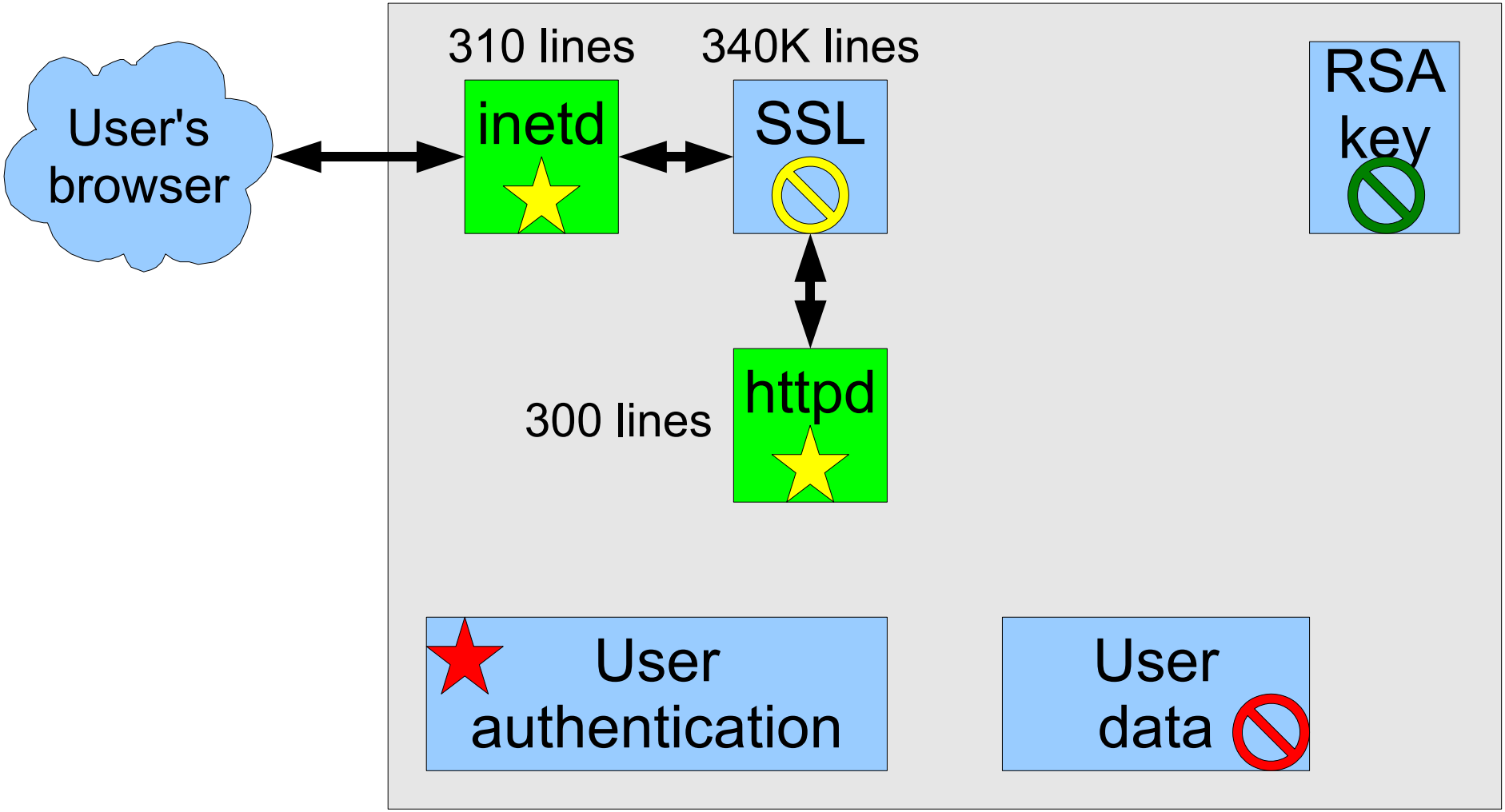


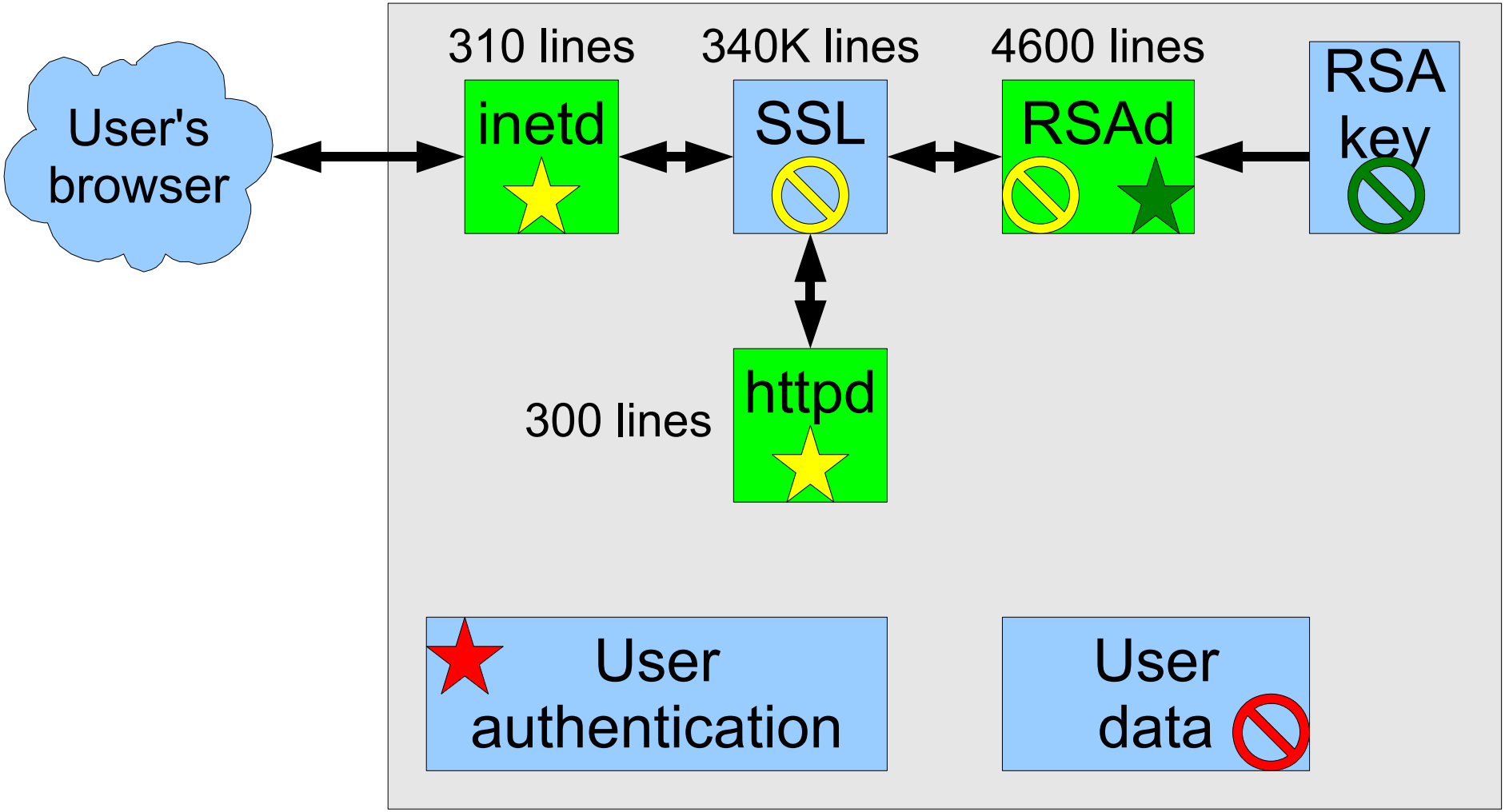
HiStar SSL Web Server

- OpenSSL only trusted to encrypt/decrypt



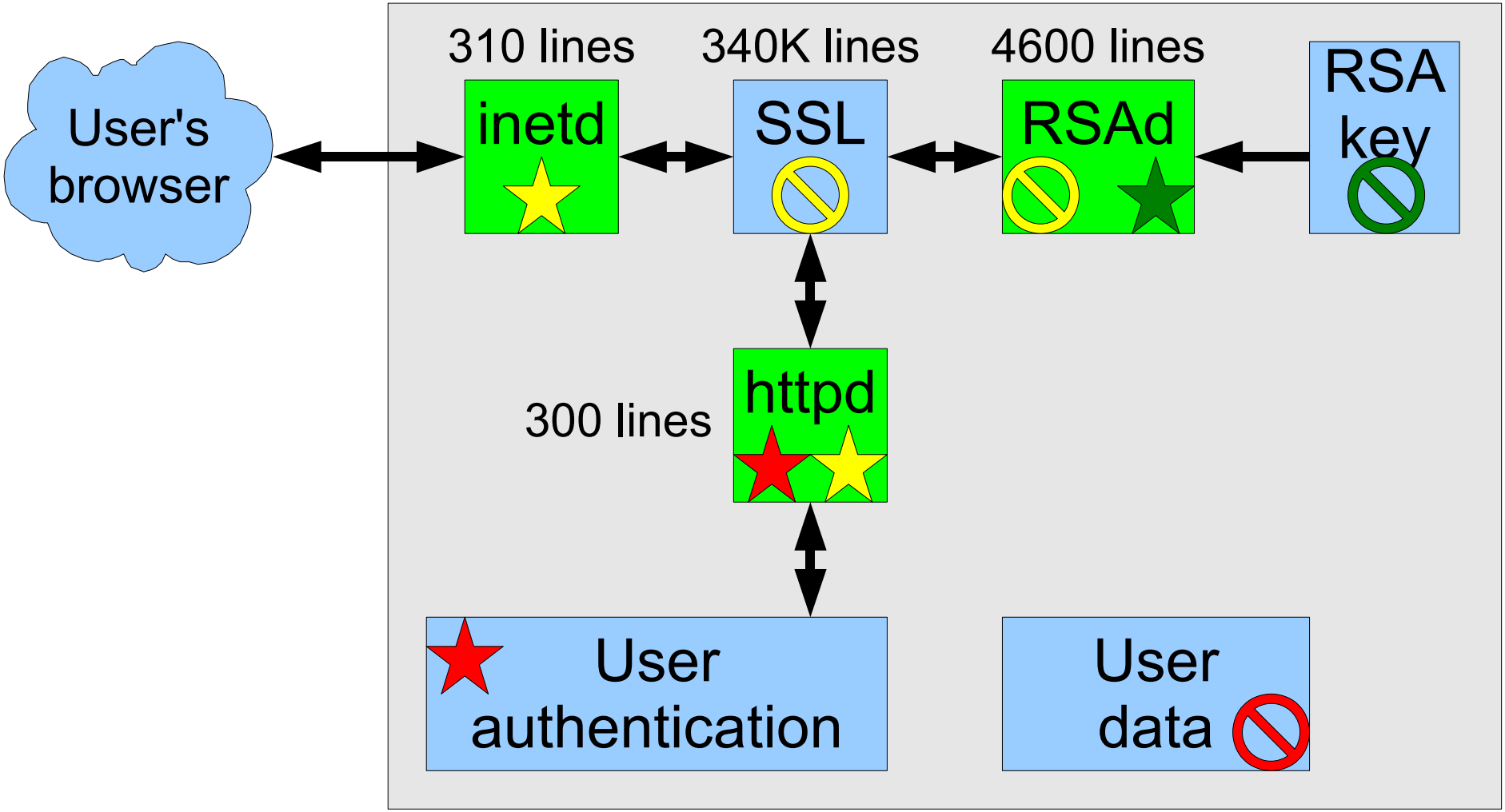
HiStar SSL Web Server

- OpenSSL cannot disclose certificate private key



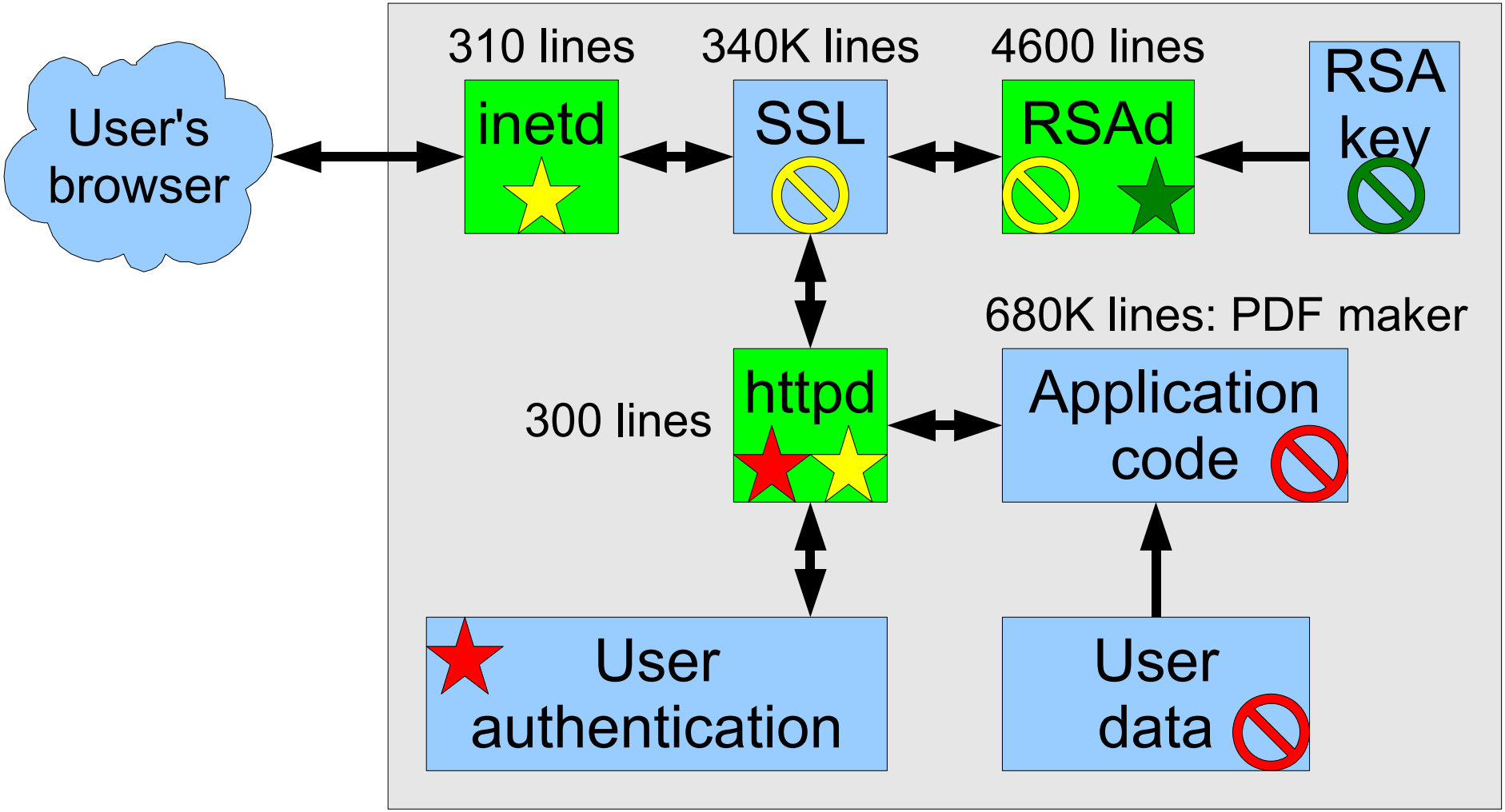
HiStar SSL Web Server

- httpd trusted with user's privilege, credentials



HiStar SSL Web Server

- Application code cannot disclose user data



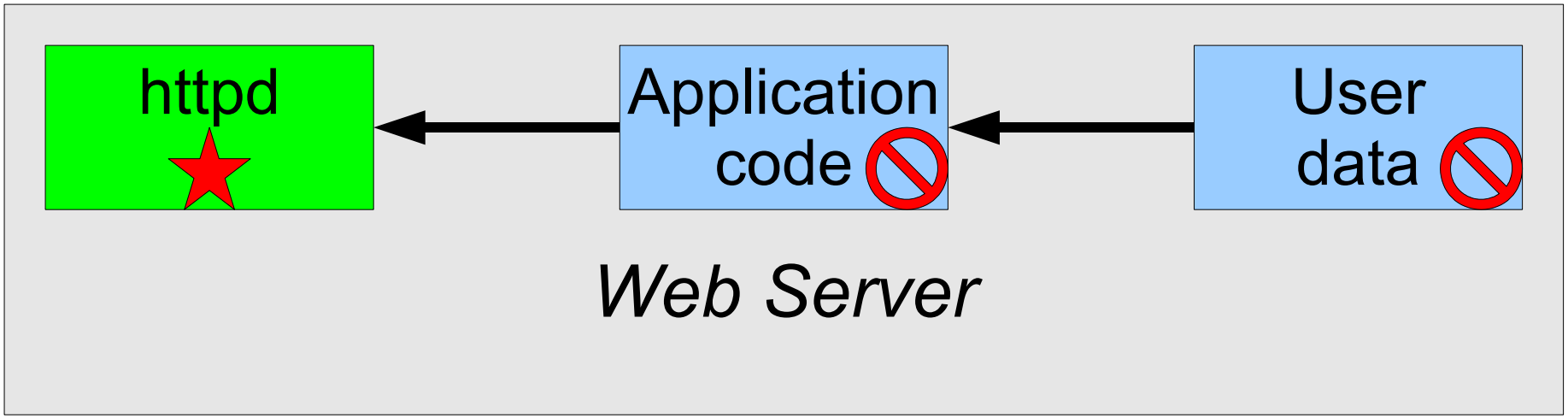
HiStar allows developers to reduce trusted code

- No code with every user's privilege during login
- No trusted code to initiate authentication
- 110-line trusted wrapper for large virus scanner
- Web server isolates different users' app code

- Small kernel: under 20,000 lines of code

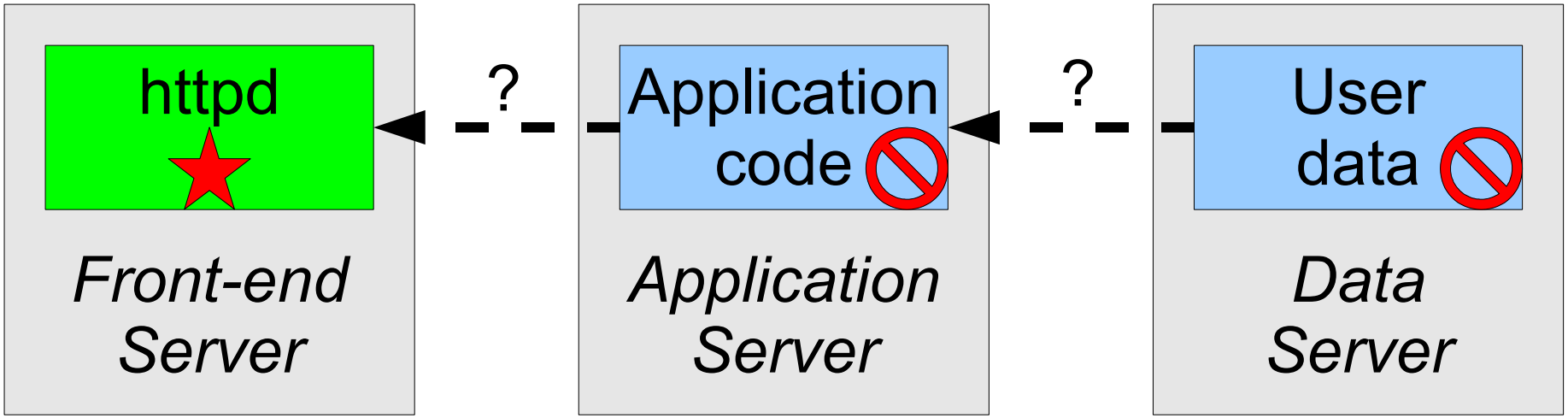
HiStar controls one machine

- Can enforce security for small web server



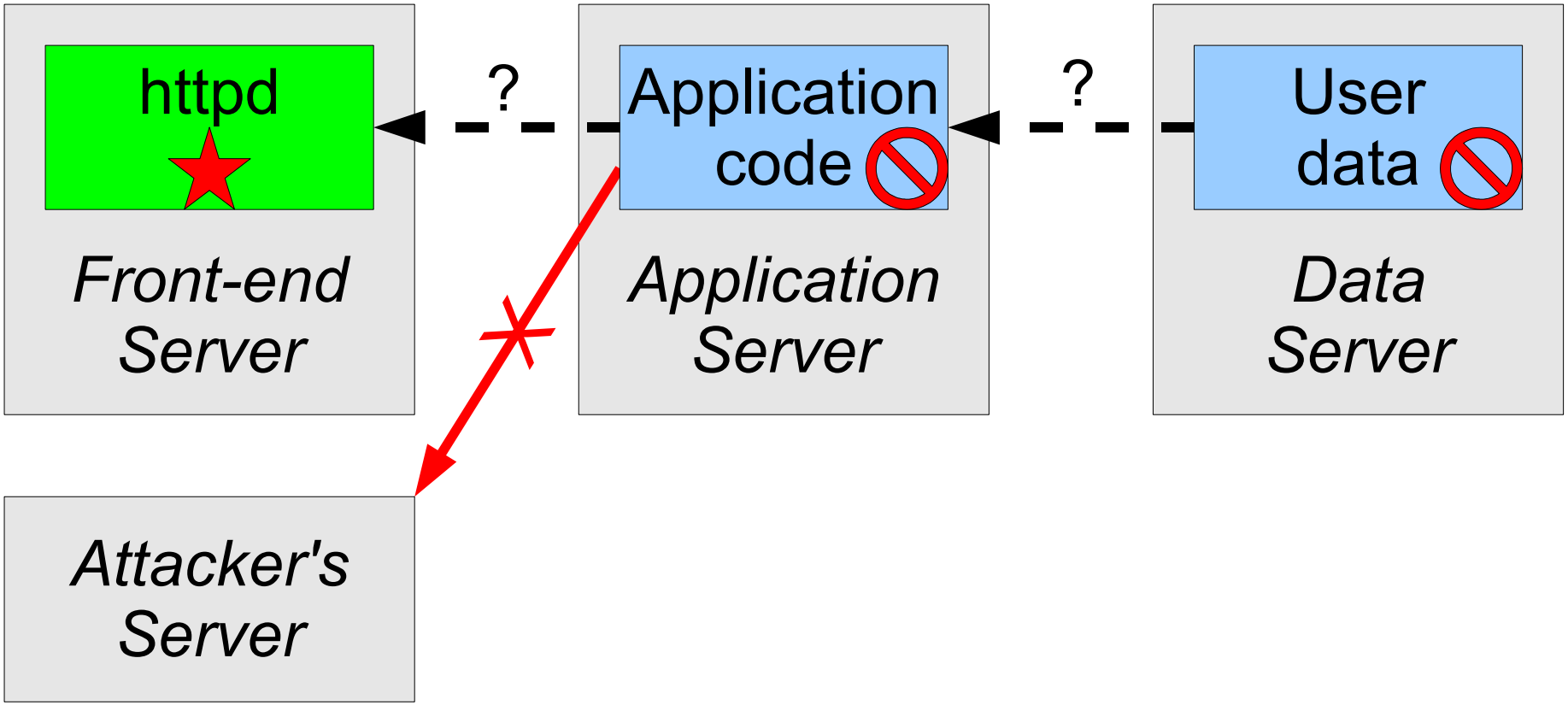
Large services are distributed

- How to track information flow across machines?



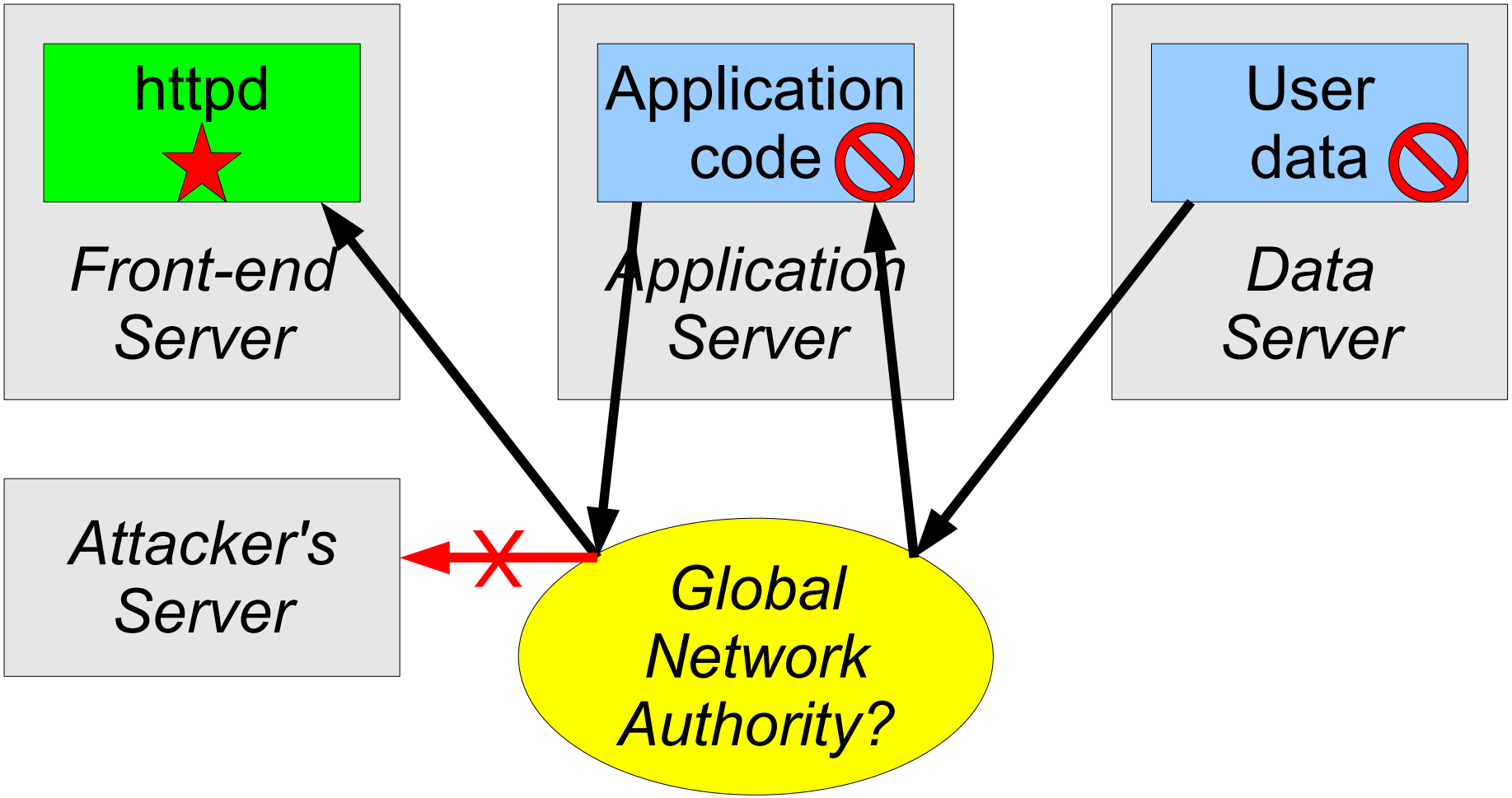
Problem: Who can we trust?

- No single fully-trusted kernel to make decisions



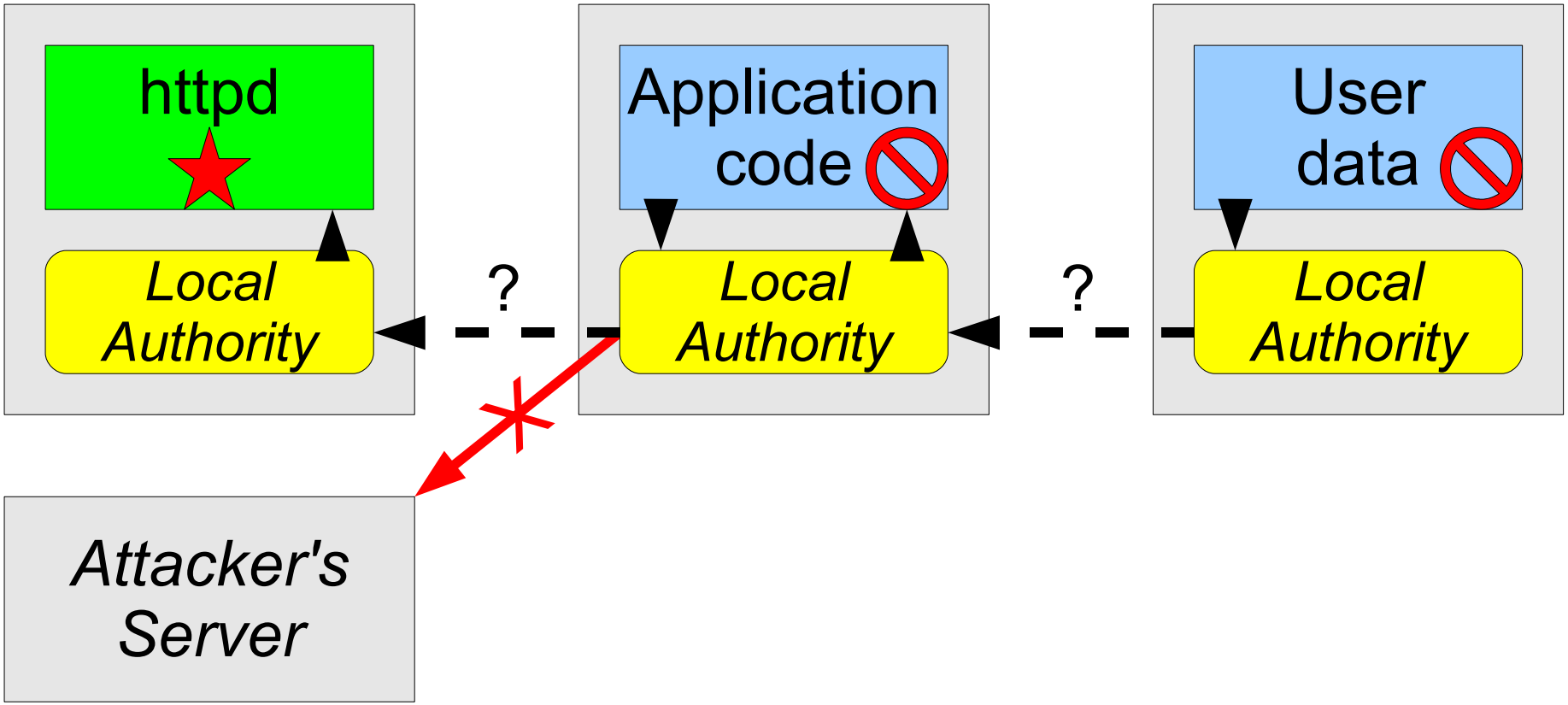
Globally-trusted authority?

- Made sense for local kernel (HiStar), but not here
  - Problems with scalability, security, trust



Decentralized design

- When it is safe to contact another machine?
  - Any query may leak information to attacker!

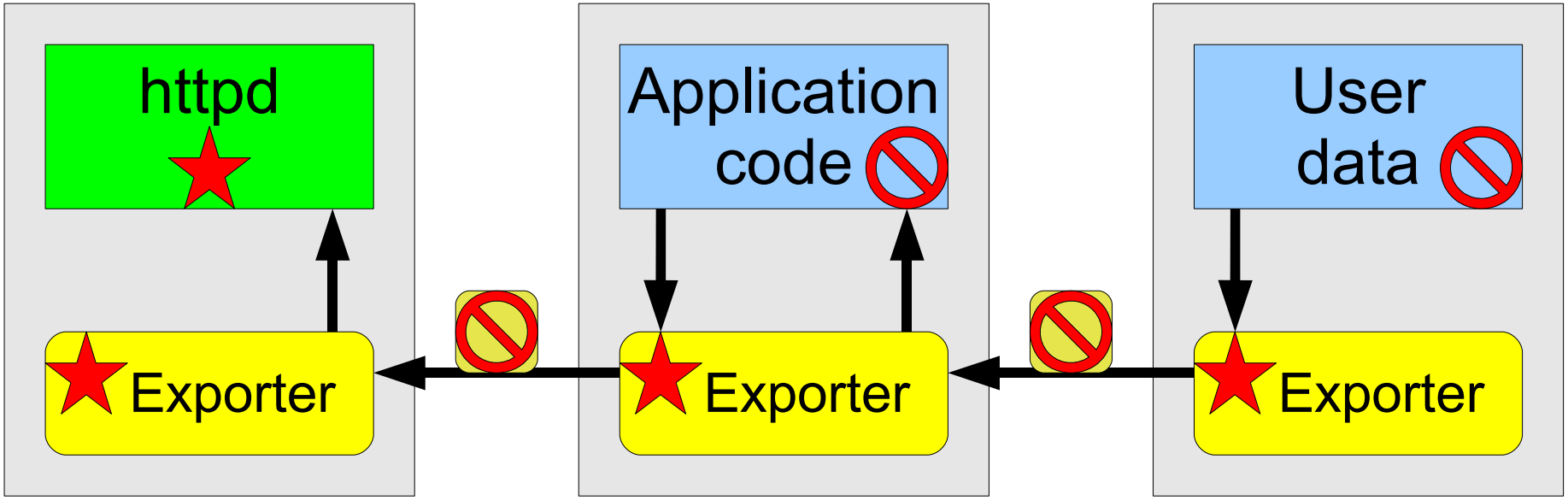


Solution: Users define trust with self-certifying categories

- Category (taint color) is a public key C
- To trust host H with your secret data, sign delegation certificate (H trusted with C) using C^{-1}
- Anyone can verify delegation certificates based on the category name (public key)

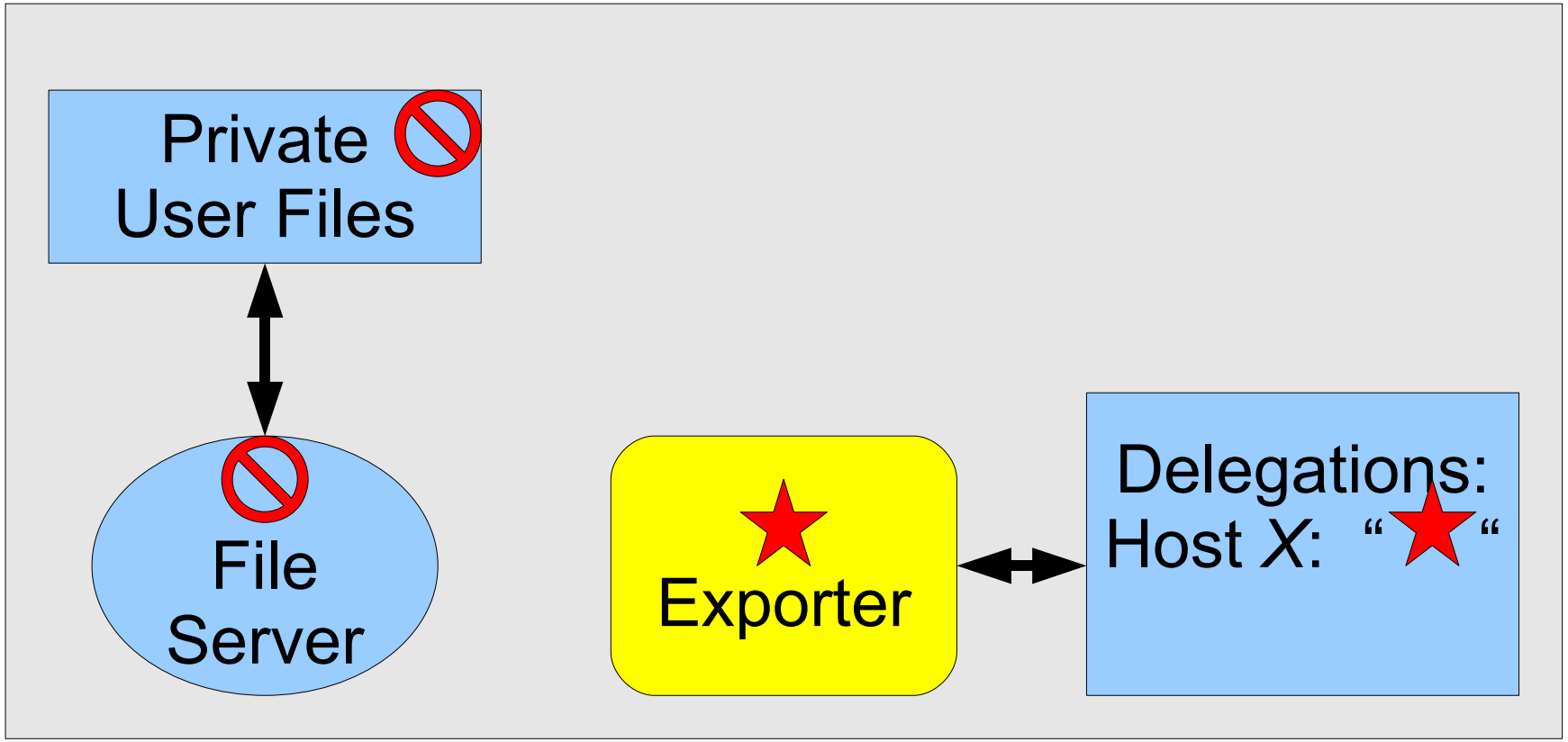
Exporter daemons

- HiStar enforces information flow locally
- Exporters send UDP-like messages with labels
  - Not part of kernel – only in TCB for distributed apps
  - Need delegations to determine if recipient is trusted



Strawman: Exporter stores delegations

- Delegation: User trusts host X with his data



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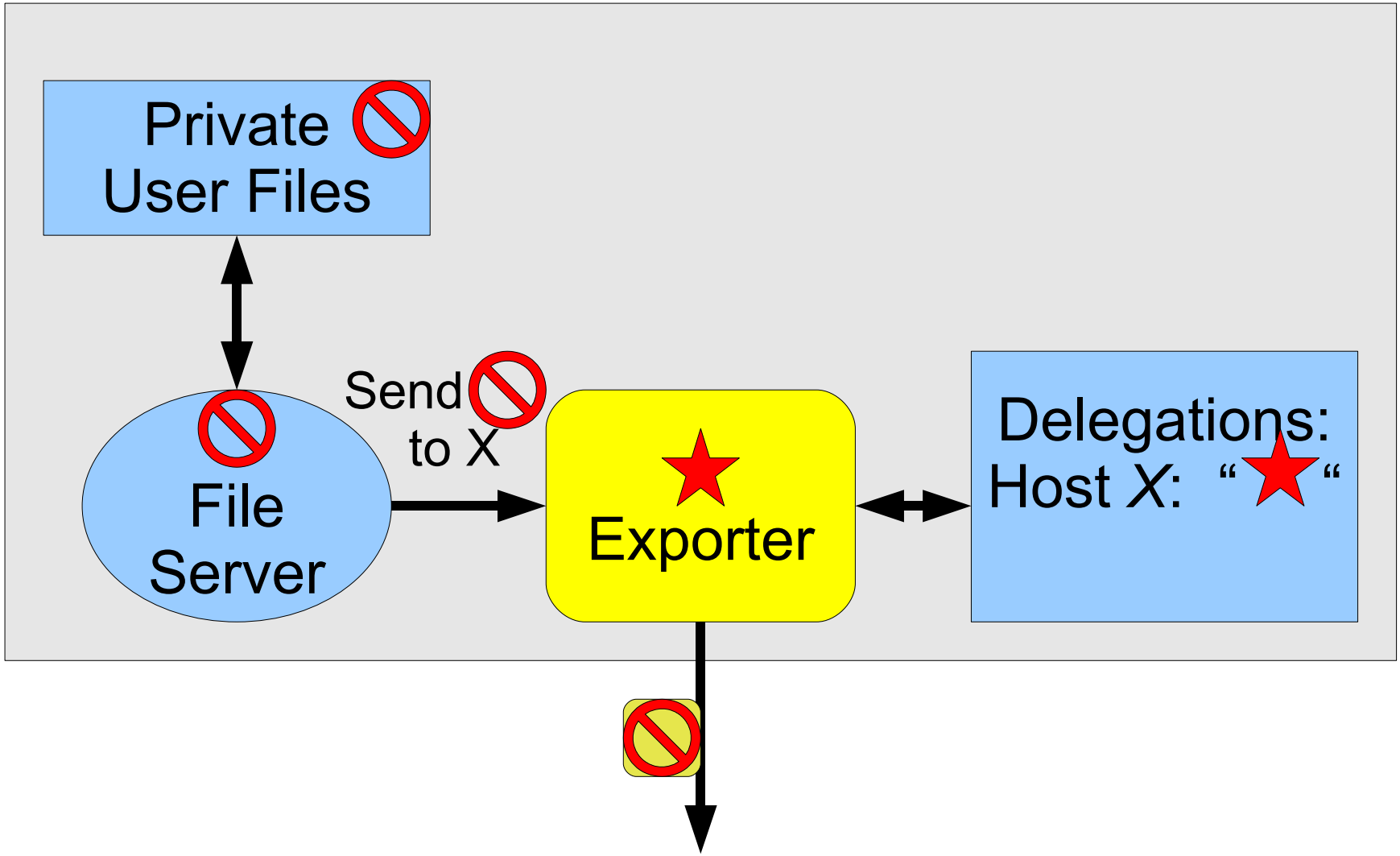
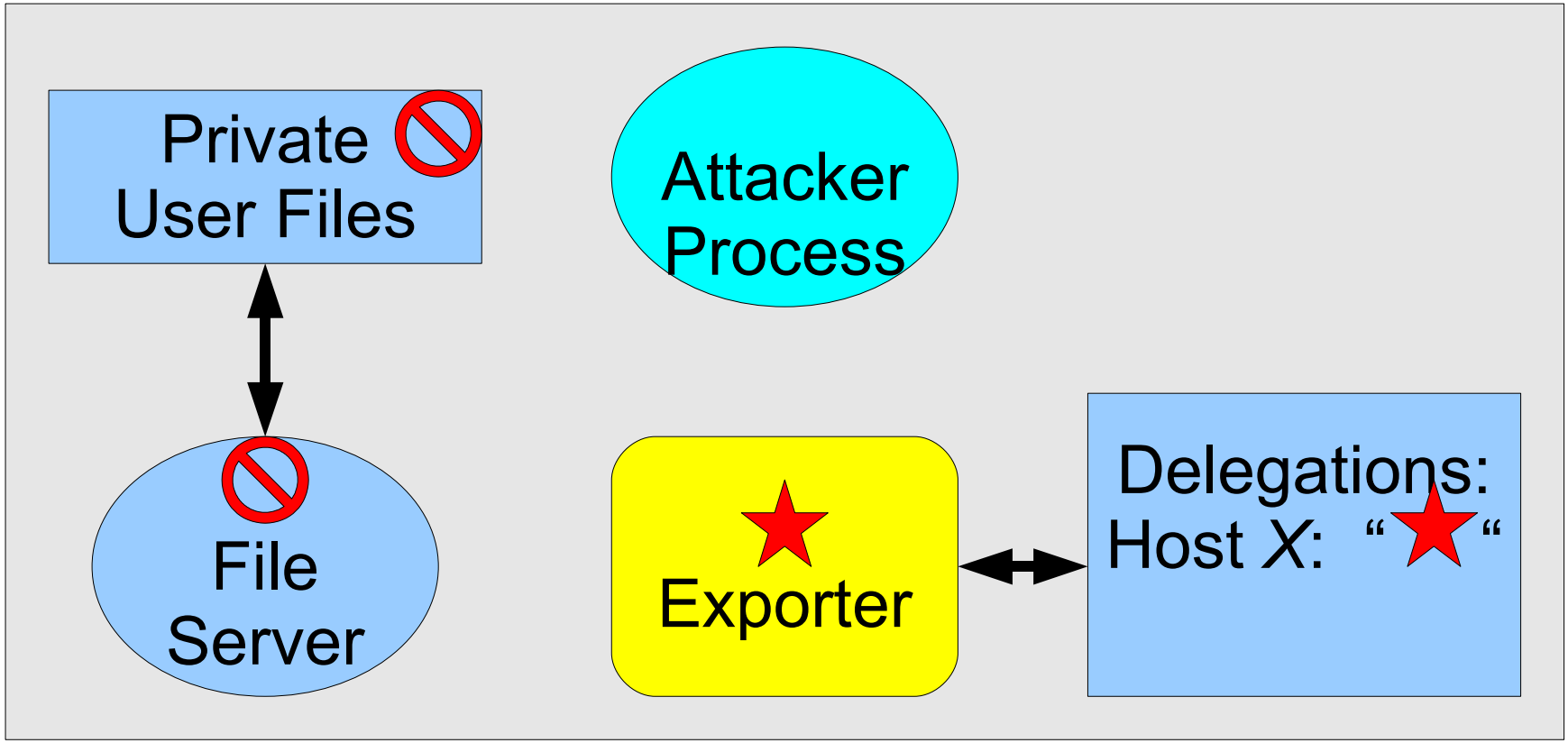


Strawman has covert channel



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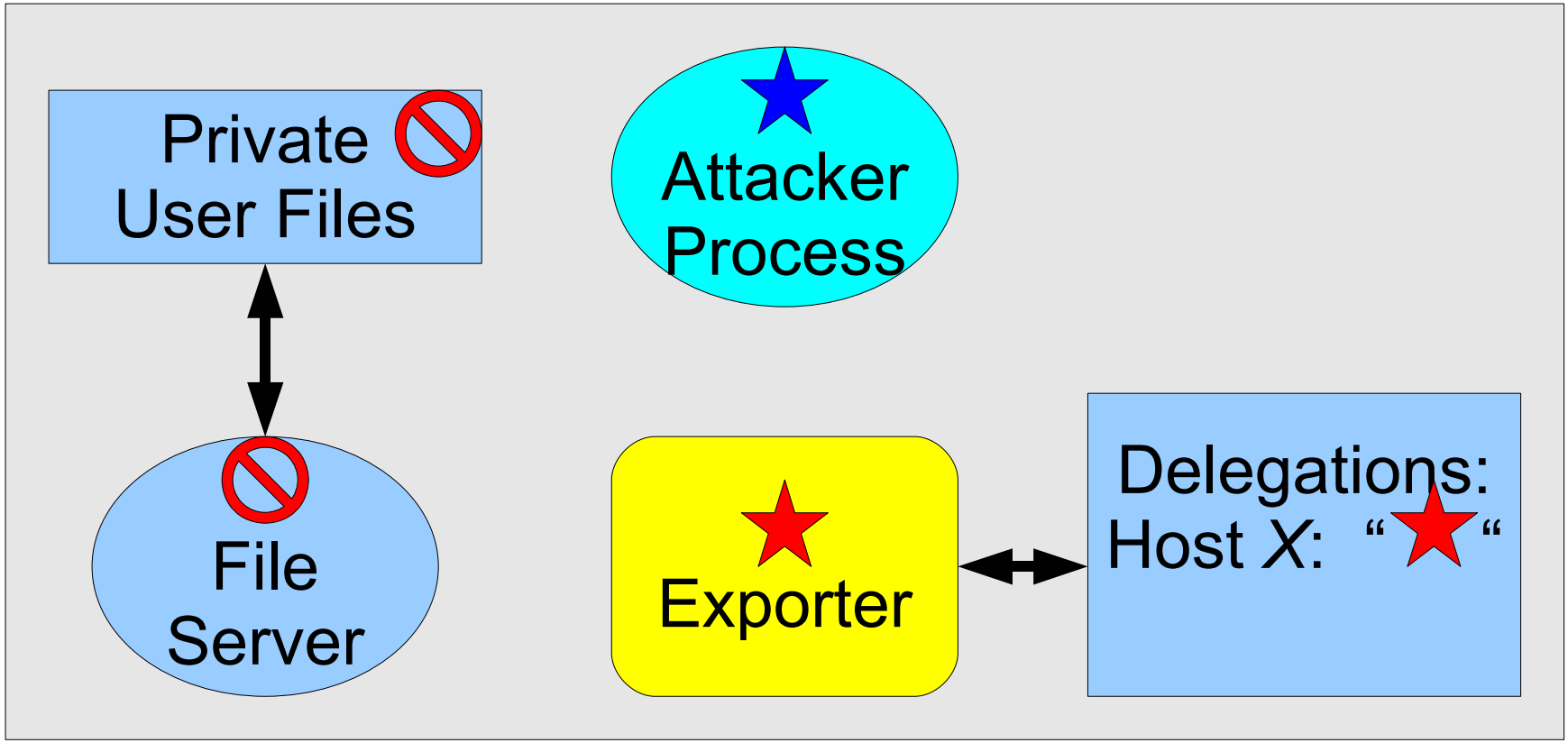

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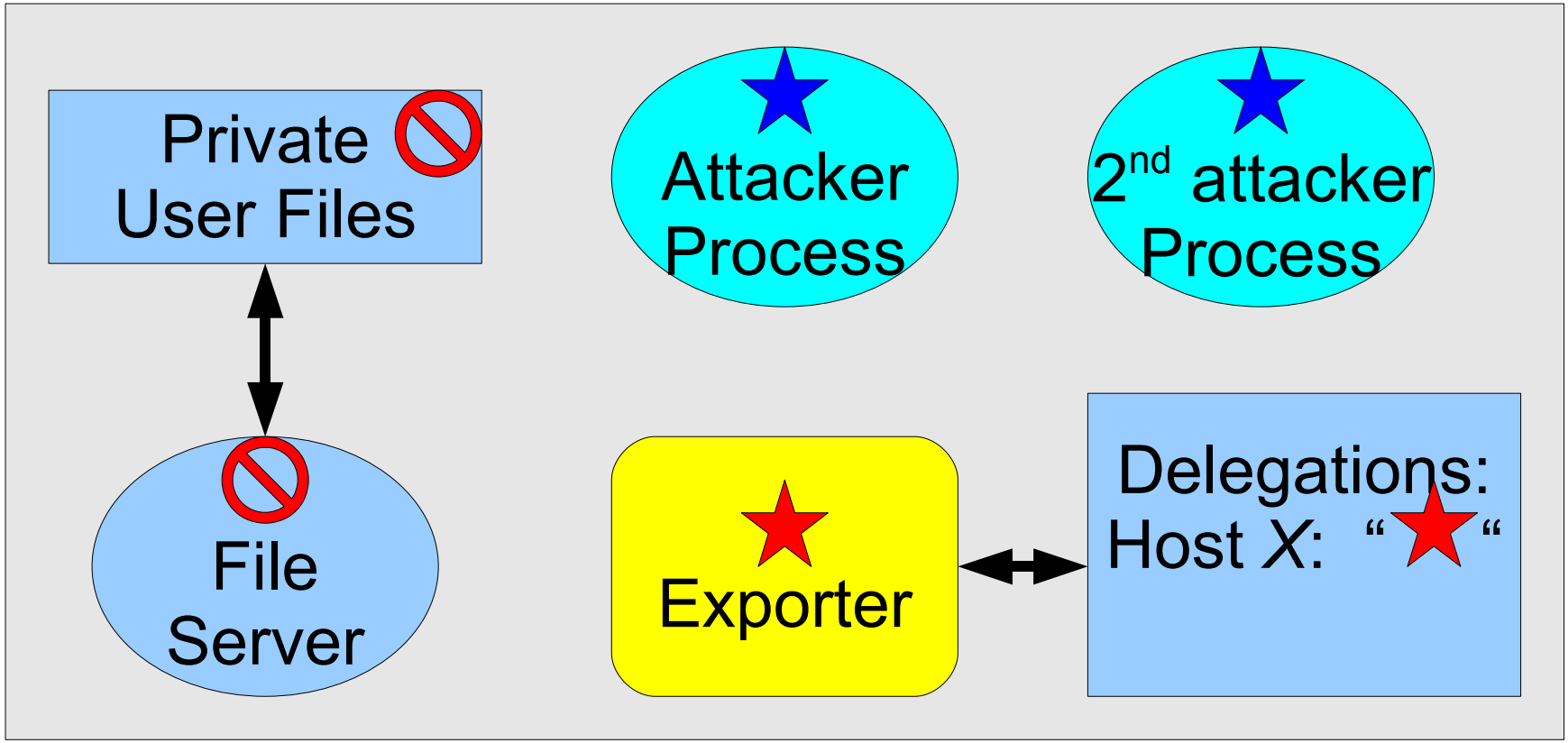

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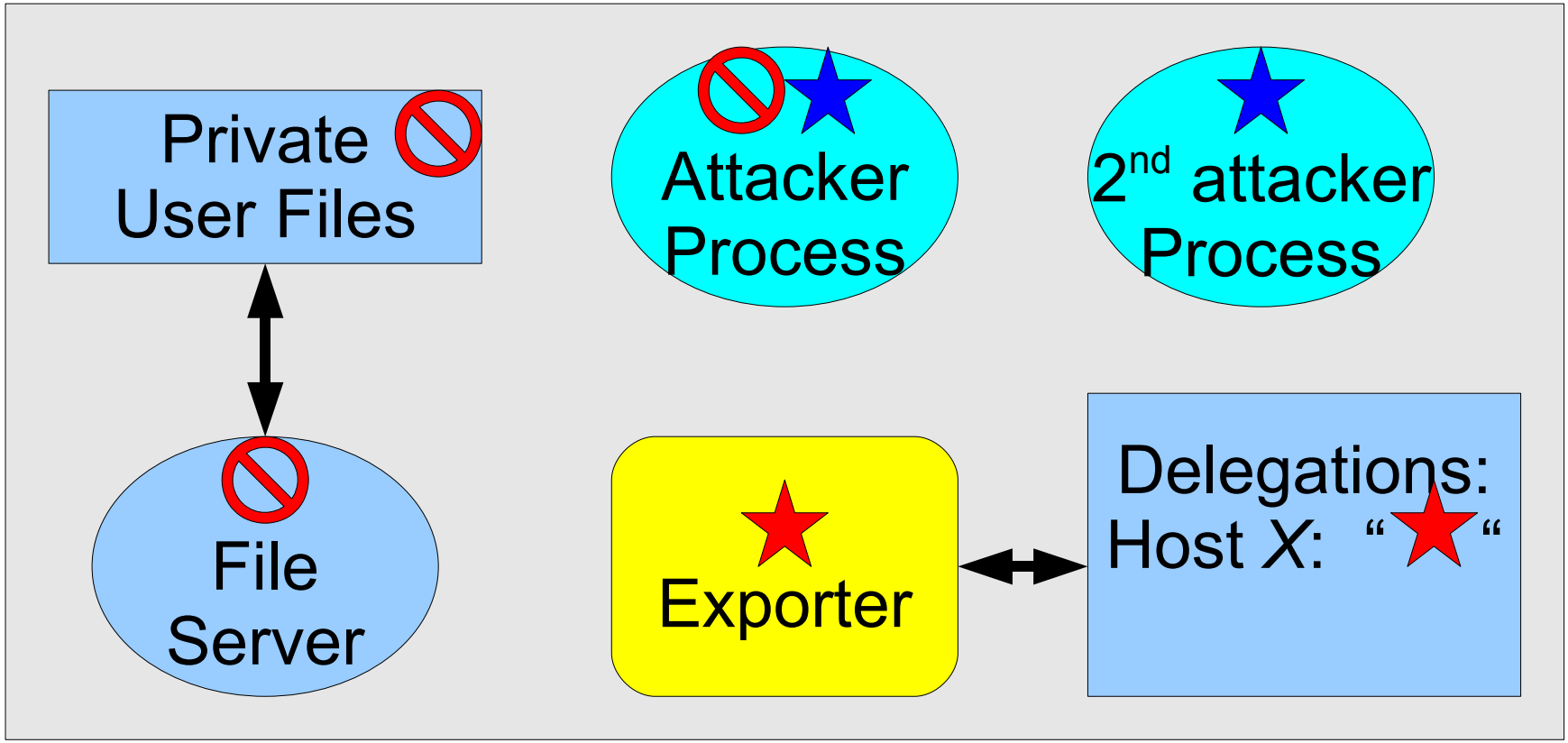

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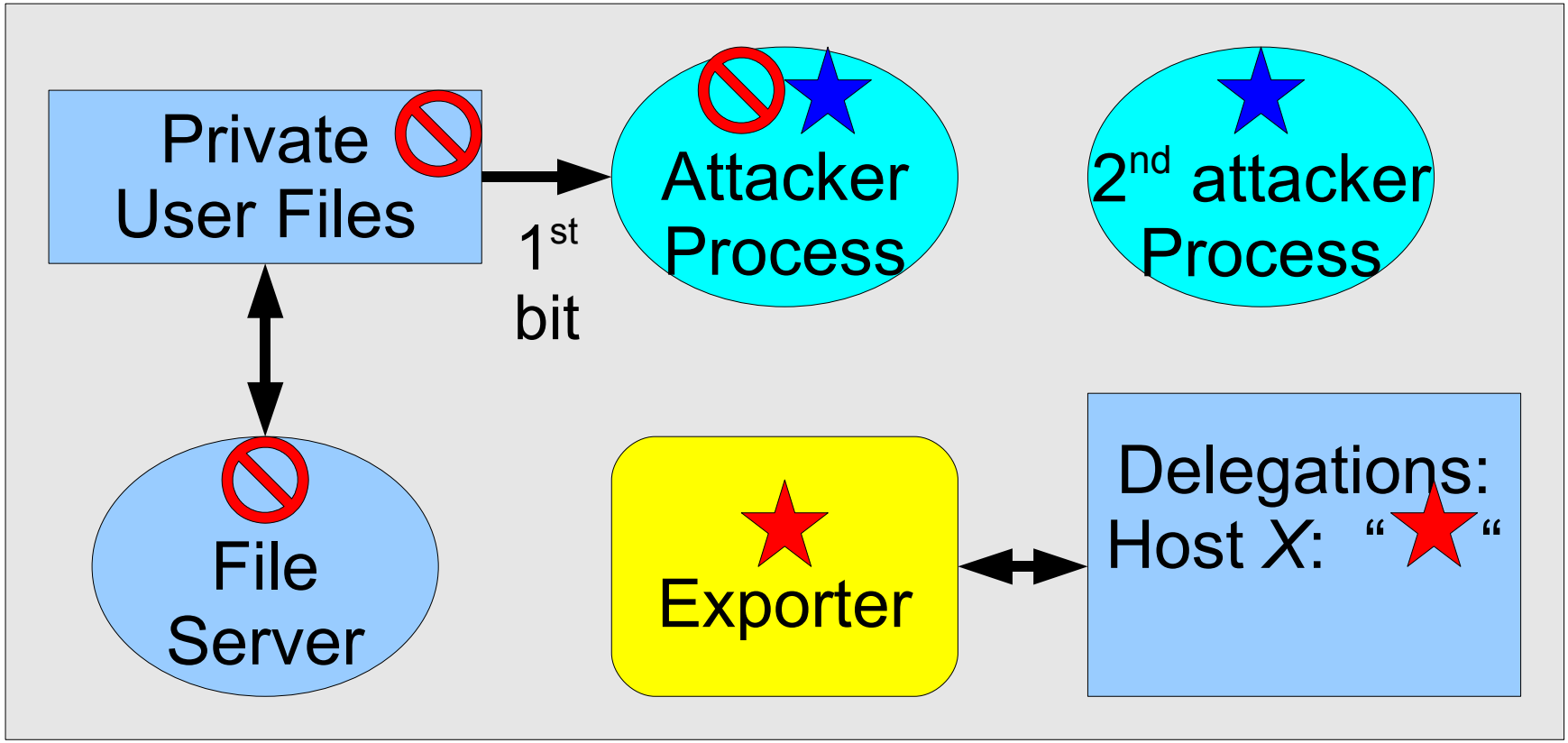

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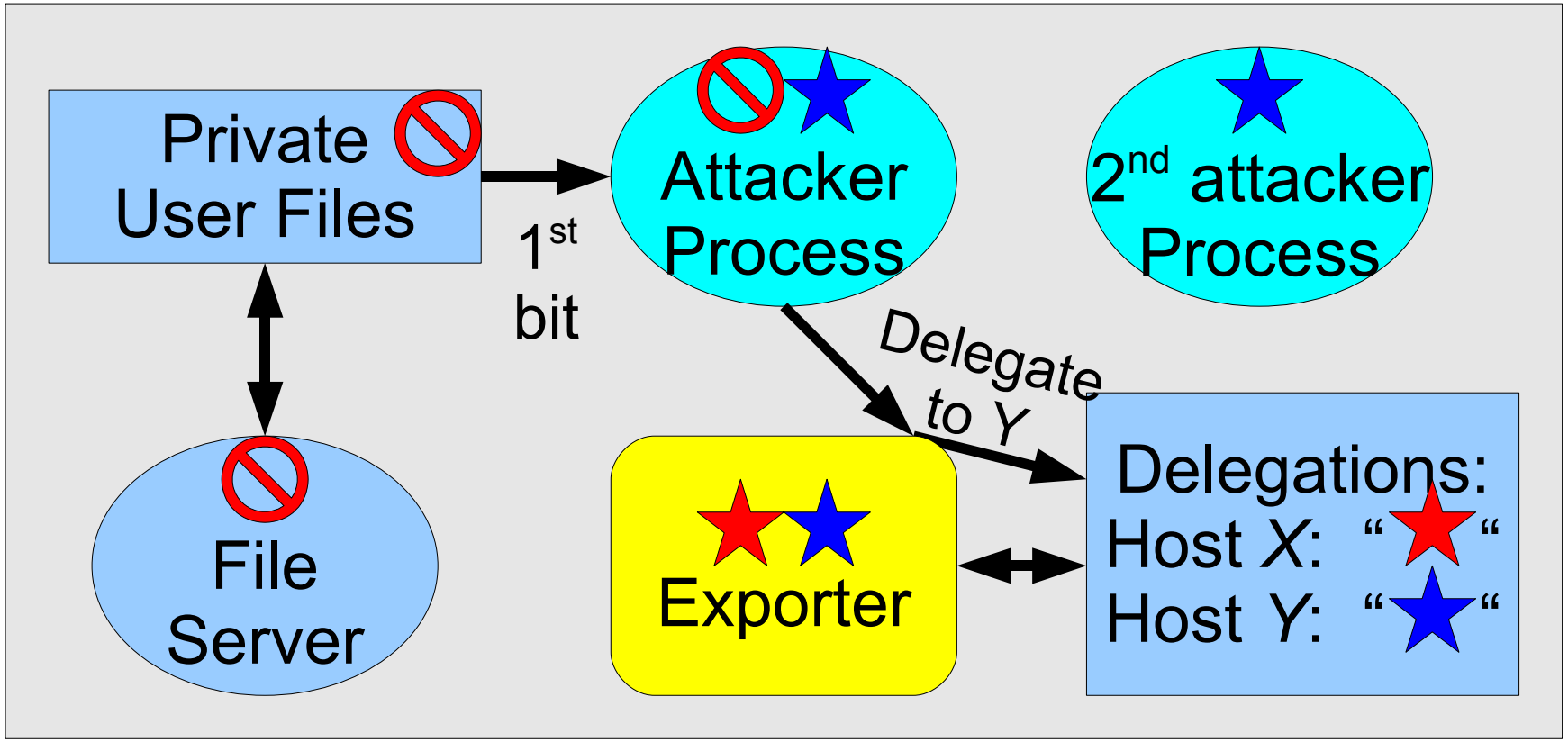

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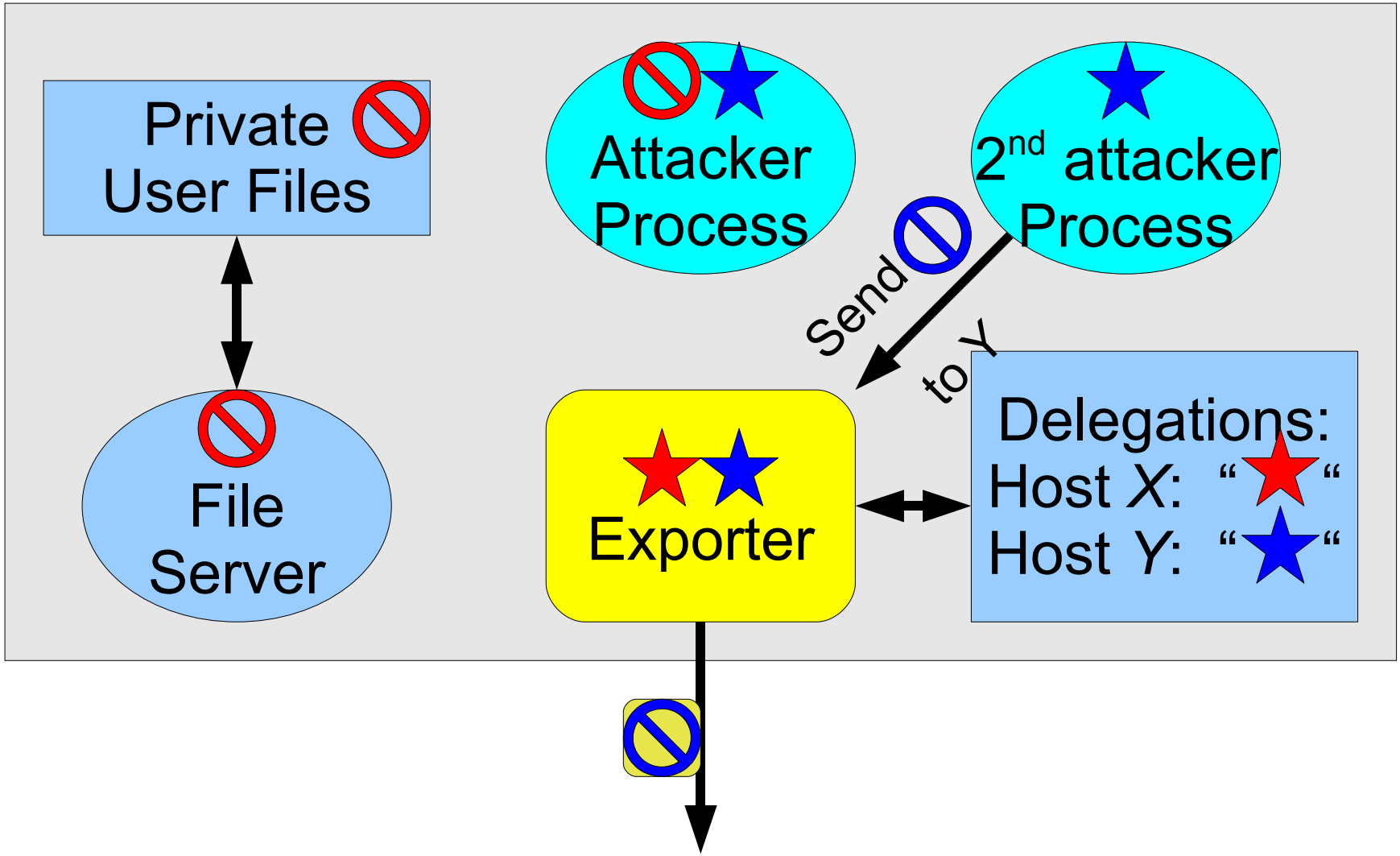
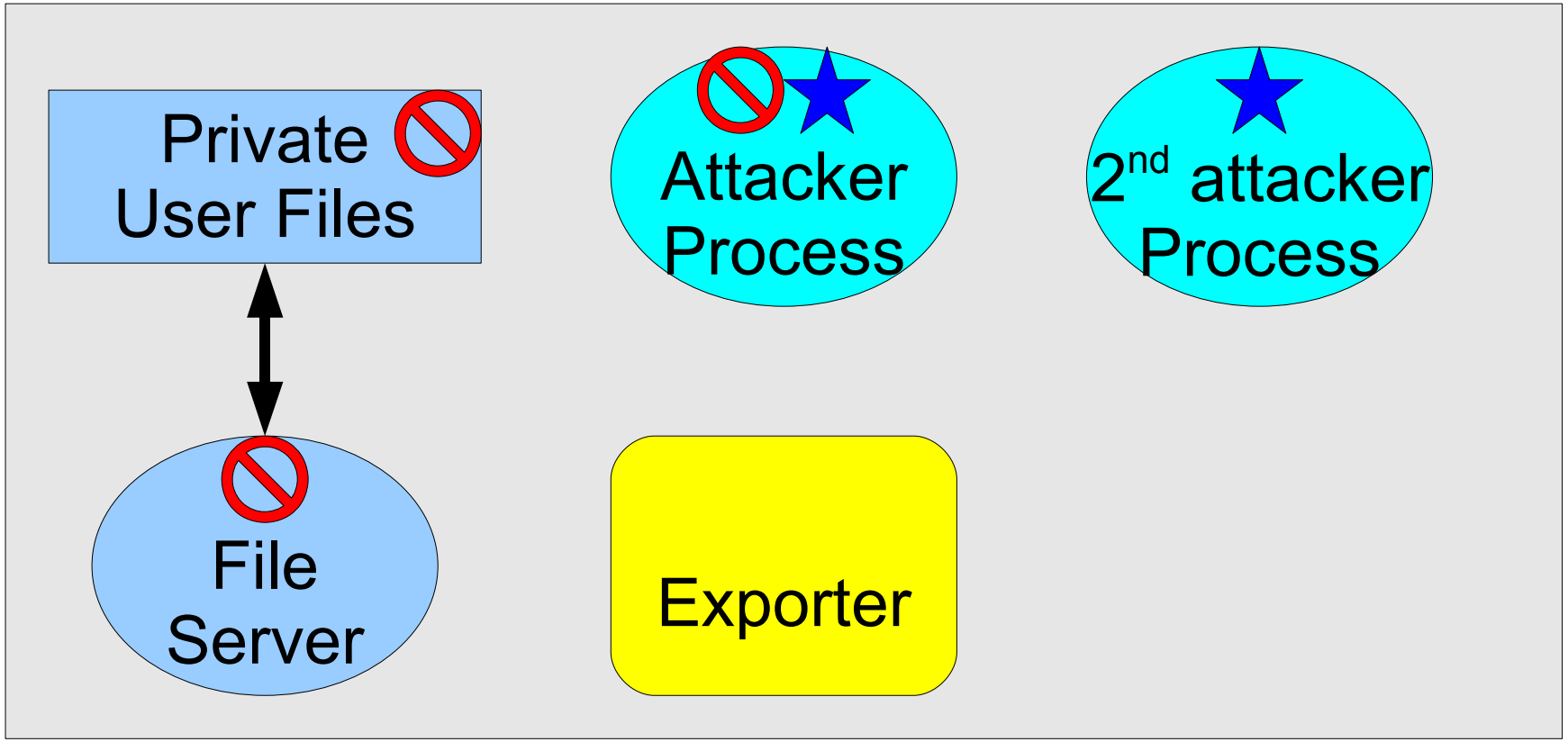


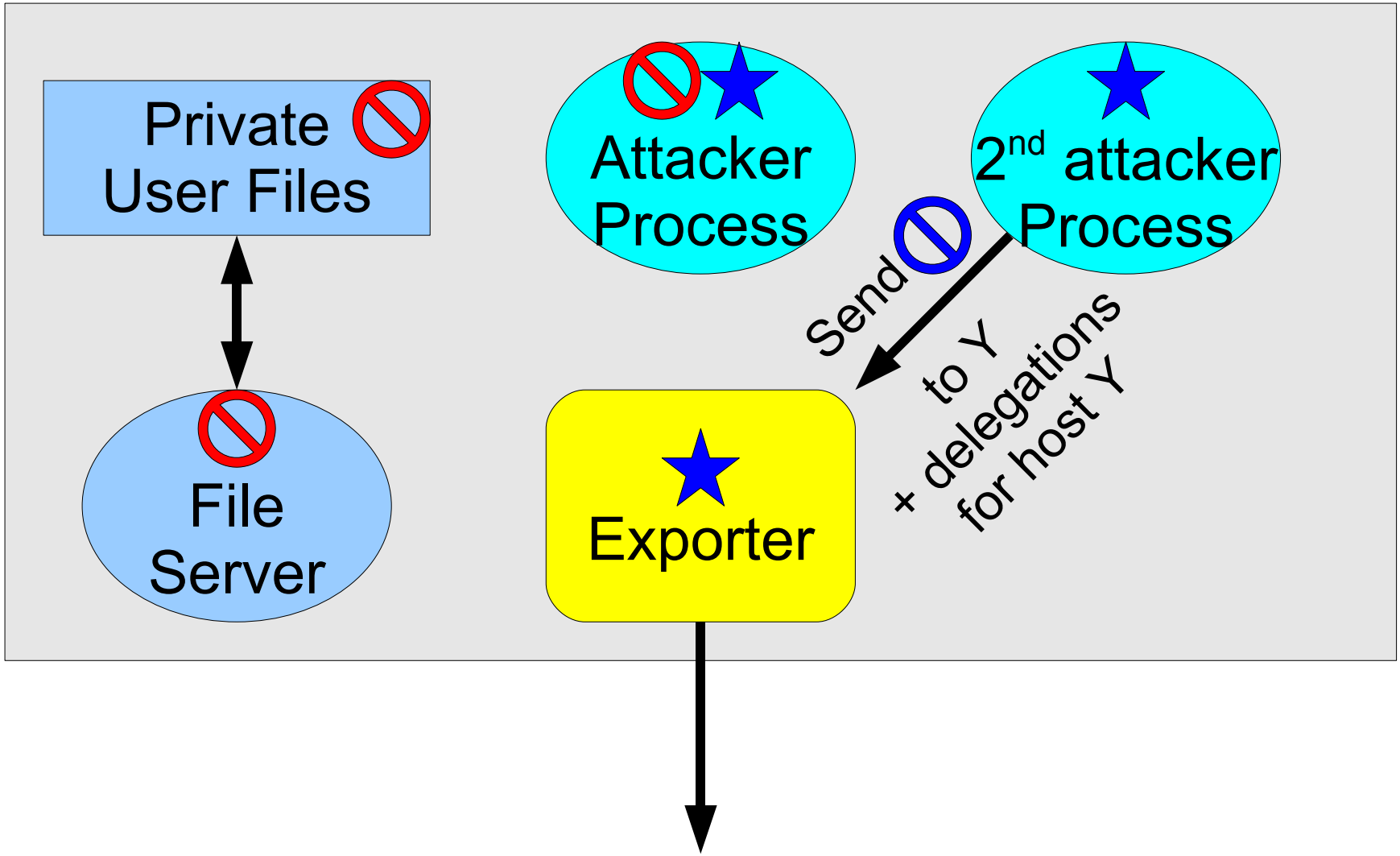
Solution: Stateless exporter

- Delegations are self-authenticating



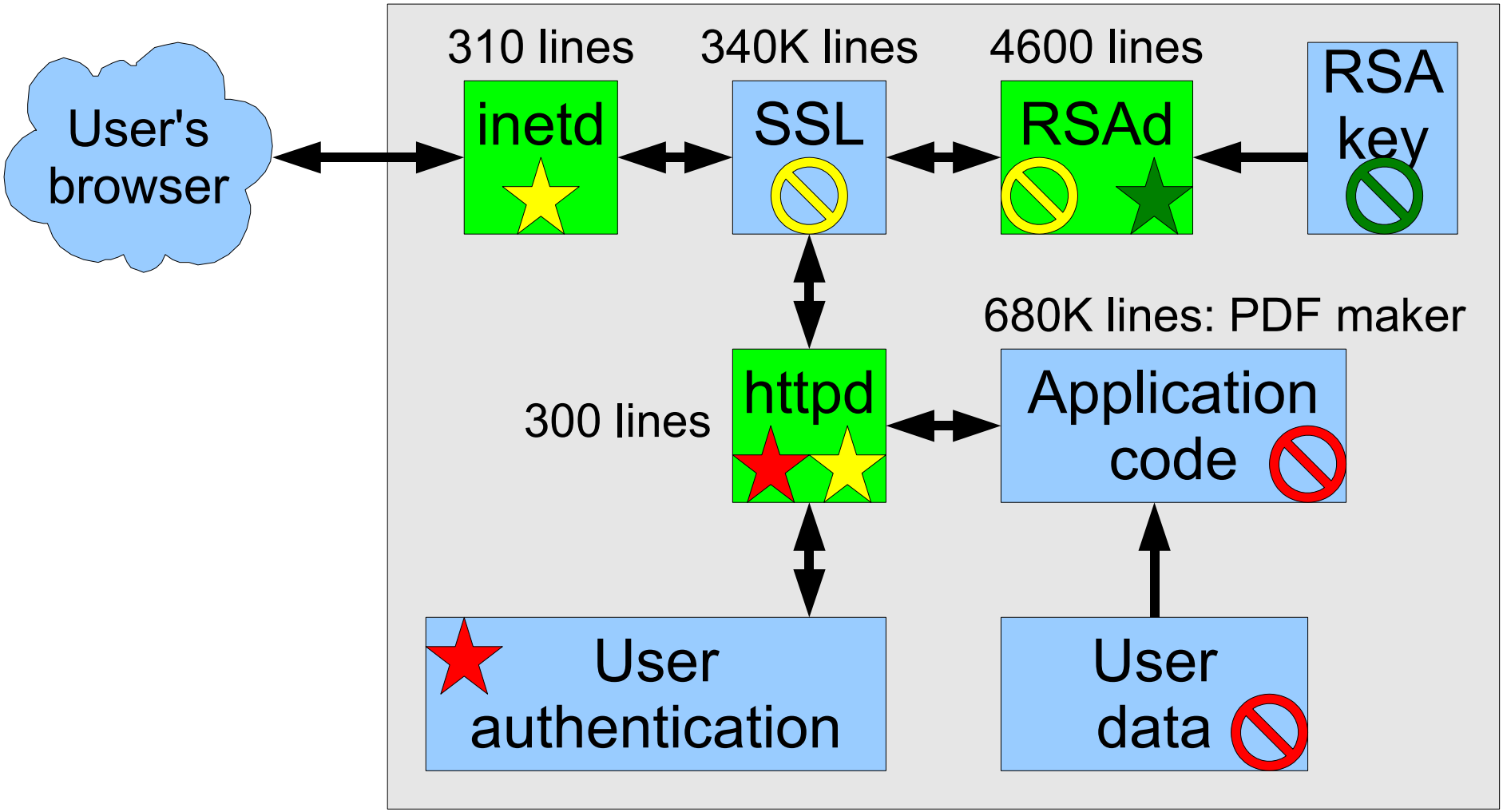
Sender supplies delegations

- Result only depends on caller-supplied data
  - Verify certificate signatures using category pub. key



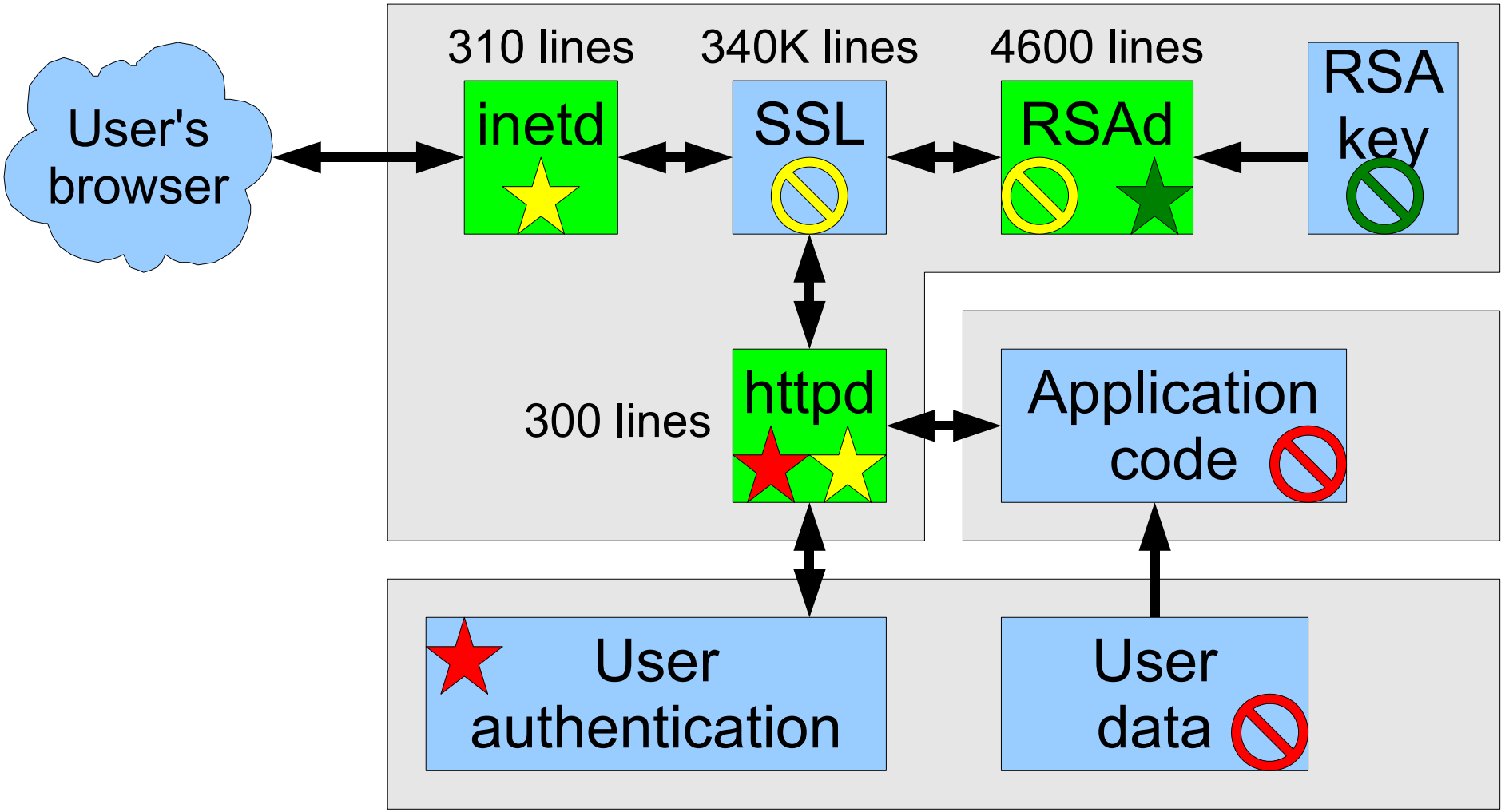
Recall: HiStar SSL Web Server

- Only small fraction of code (green) is trusted



Scalable, Distributed Web Server

- Same security properties (except trust exporters)
  - No fully-trusted machines: limits effect of compromise

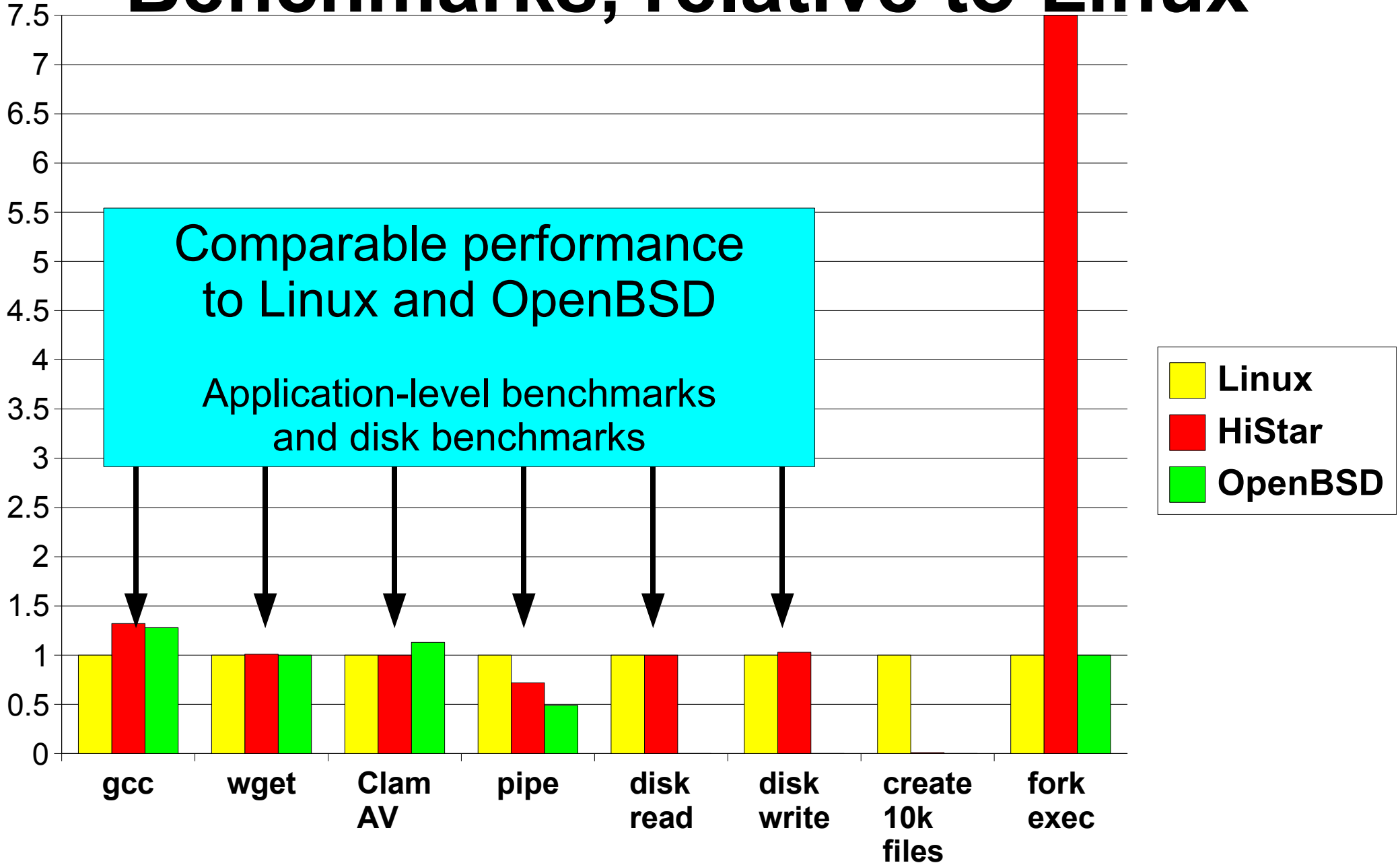


Conclusion

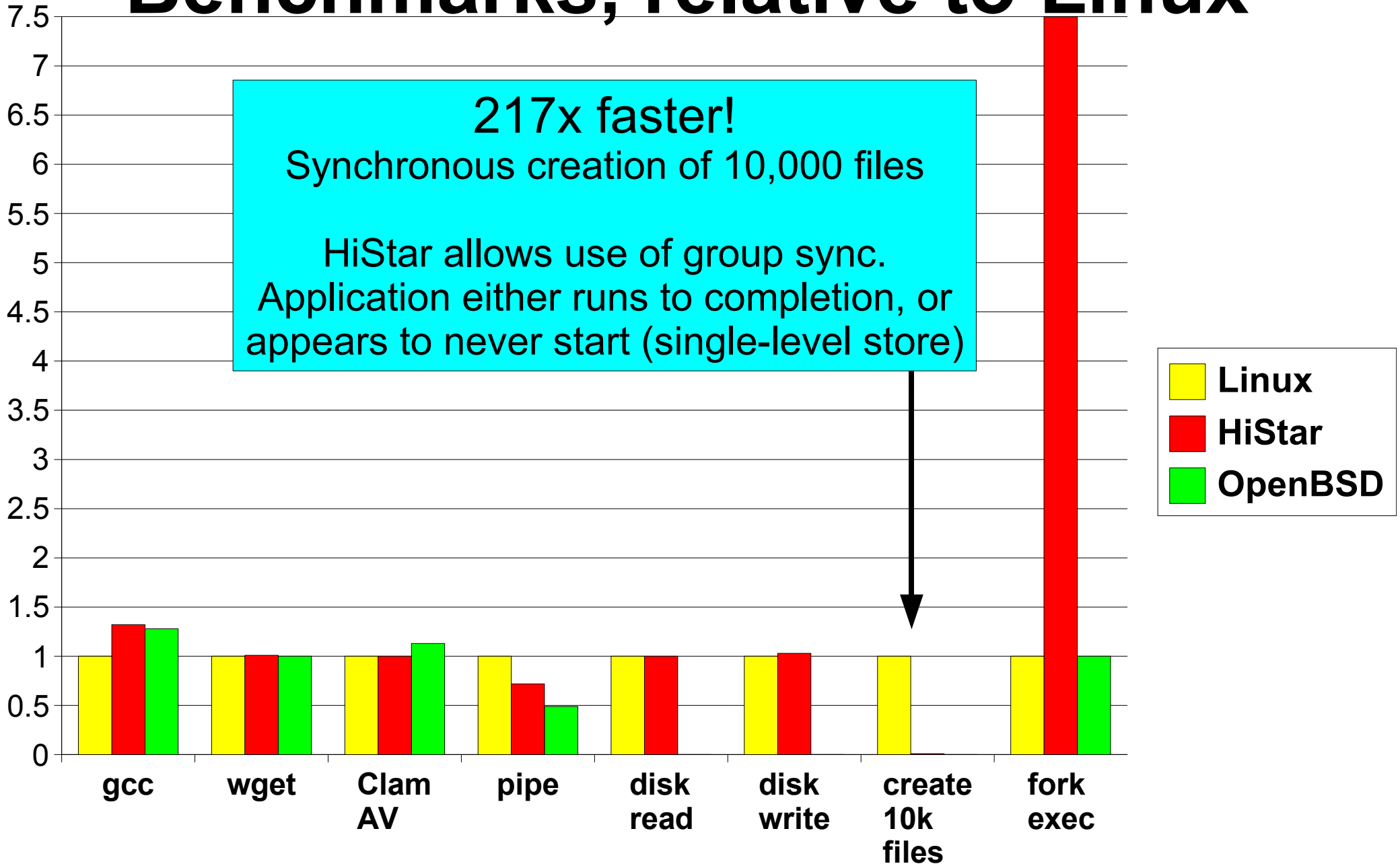
- HiStar reduces amount of trusted code
  - Safely run untrusted code on confidential data
- Kernel interface eliminates covert channels
  - Make everything explicit: labels, resources
- Unix library makes Unix information flow explicit
  - Superuser by convention, not by design
- No fully-trusted machines in distributed system

`http://www.scs.stanford.edu/histar/`

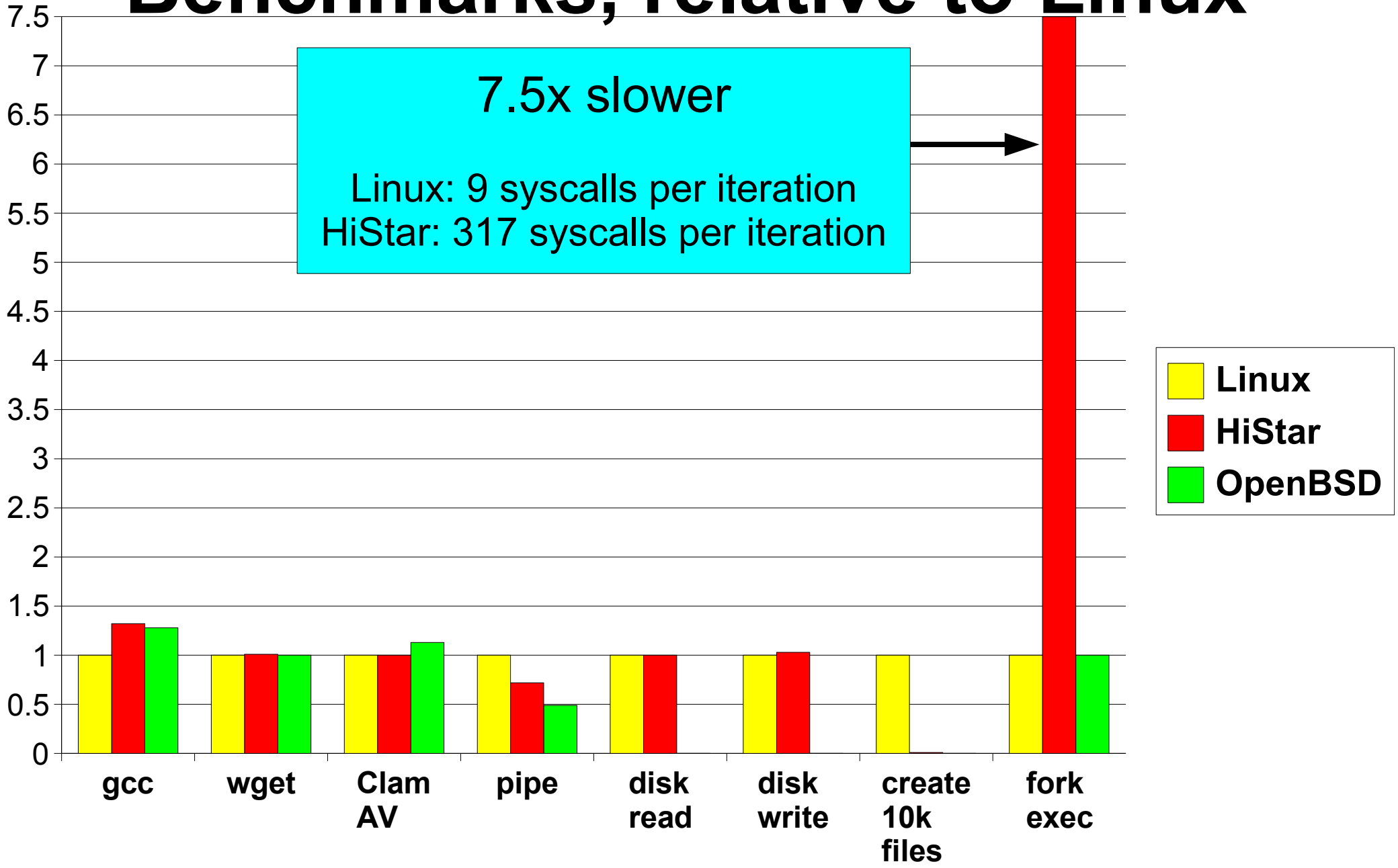
Benchmarks, relative to Linux



Benchmarks, relative to Linux

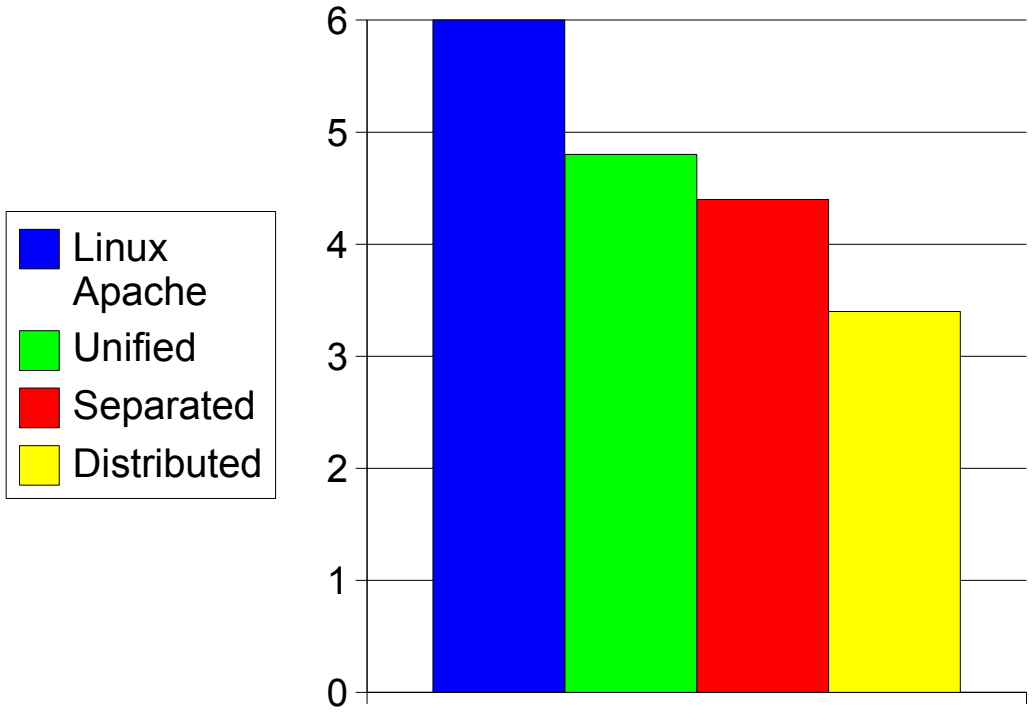


Benchmarks, relative to Linux



Web server: “PDF maker” app

Throughput on one server, req / second



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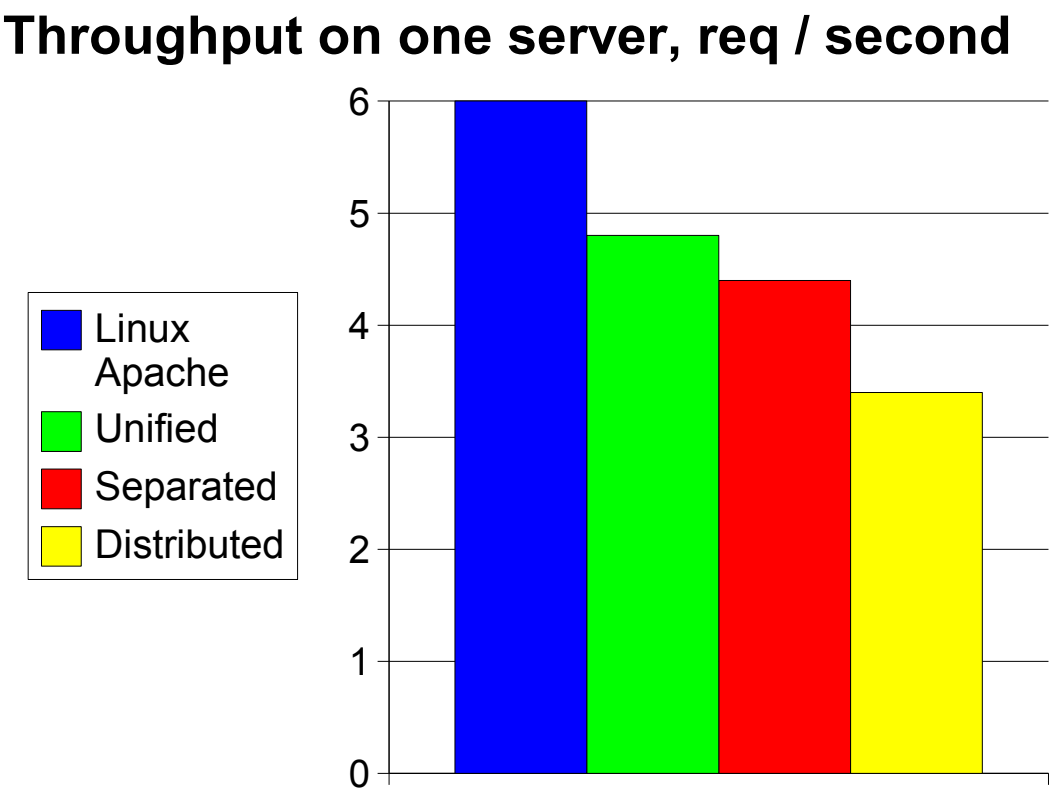

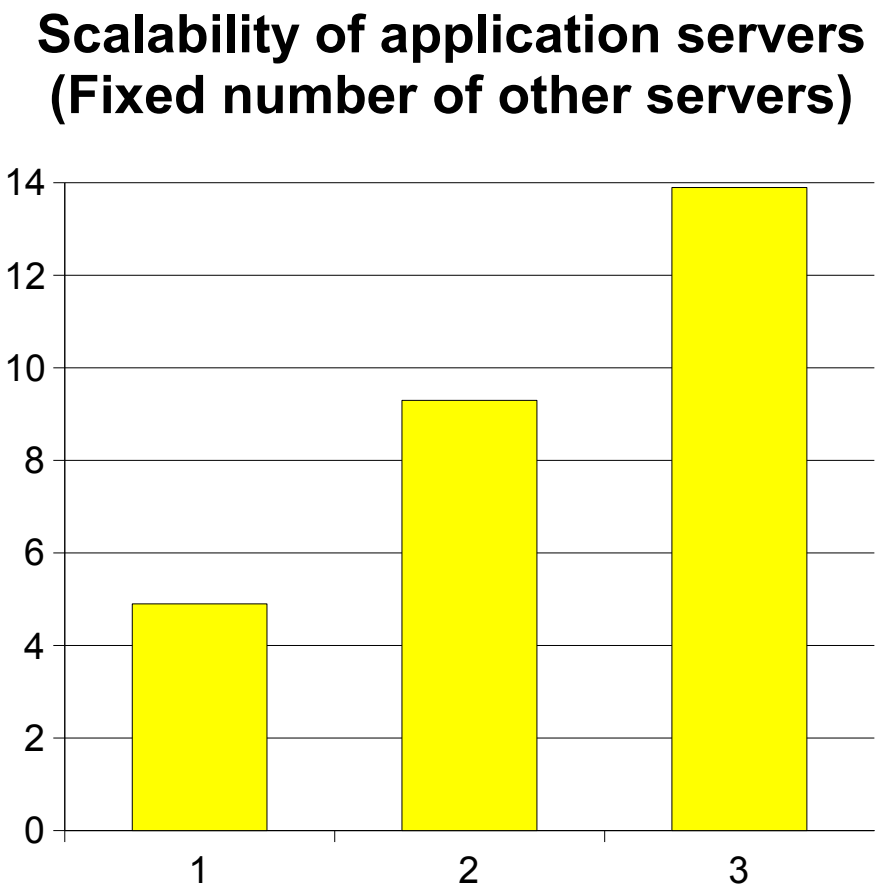

Language-based security

- Much more fine-grained control
- Resource allocation covert channels hard to fix
- Similar problems in structuring code
  - ```
    if (secret == 1)
        foo();
    printf("Hello world.\n");
    ```
  - If `secret` is tainted, `foo` runs tainted
  - `printf` only runs if `foo` terminates
  - Must prove that `foo` halts to remove taint on thread
    ```

Labels vs capabilities

- Both provide strong isolation

- Capabilities: determine privilege before starting
  - Restricts program structure
- Labels: can change privilege levels at runtime
  - Thread can raise label to read a secret file
  - Label change prevents writing to non-secret files
  - Easier to apply to existing code

Labels in a capability OS