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
- CardSystems loses 40,000,000 CC numbers
- Secret service mail stolen from T-mobile
- 10,000 users compromised at Stanford (CDC)
- Don't these people know what they're doing?

Problem: Bad Code

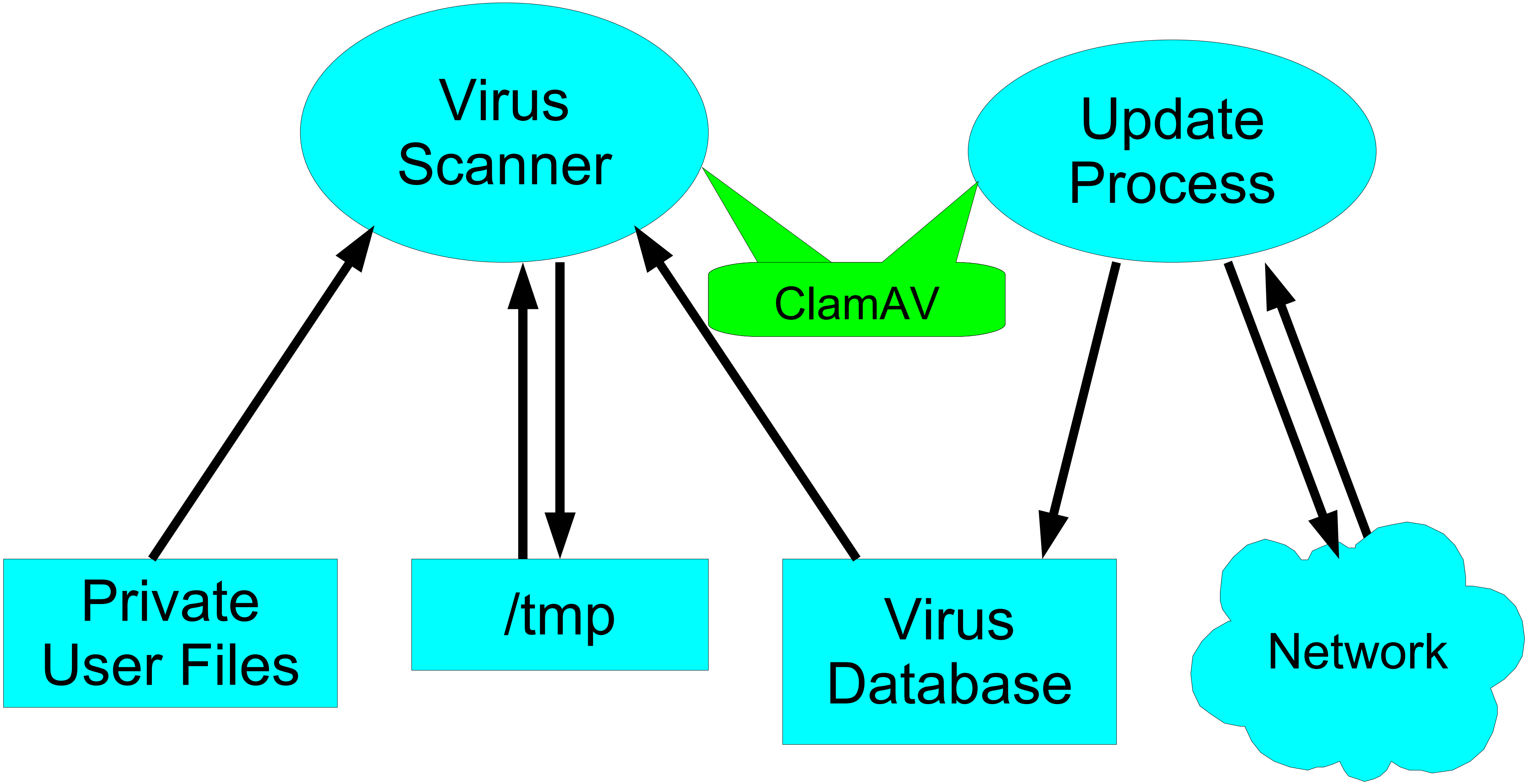
- Even *security experts* can't get it right
- May 2006: Symantec AV 10.x remote exploit
  - Software deployed on 200,000,000 machines
  - Without this software, machines also vulnerable
  - You just can't win
- If *Symantec* can't get it right, what hope is there?

Solution: Give up

- Accept that software is untrustworthy
- Legitimate software is often vulnerable
- Users willingly run malicious software
  - Malware, spyware, ...
- No sign that this problem is going away
- Make software less trusted

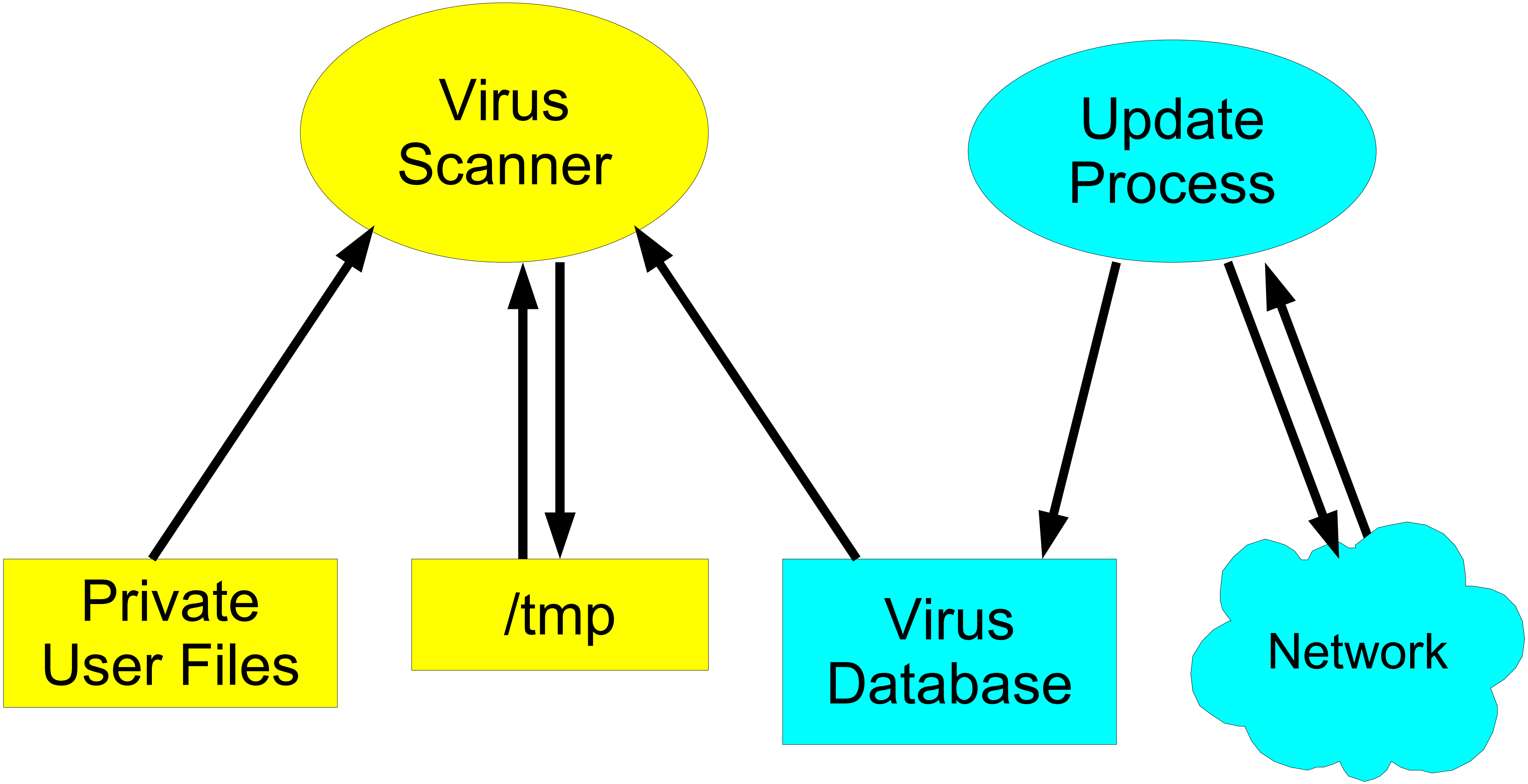
Example: Virus Scanner

Goal: private files cannot go onto the network

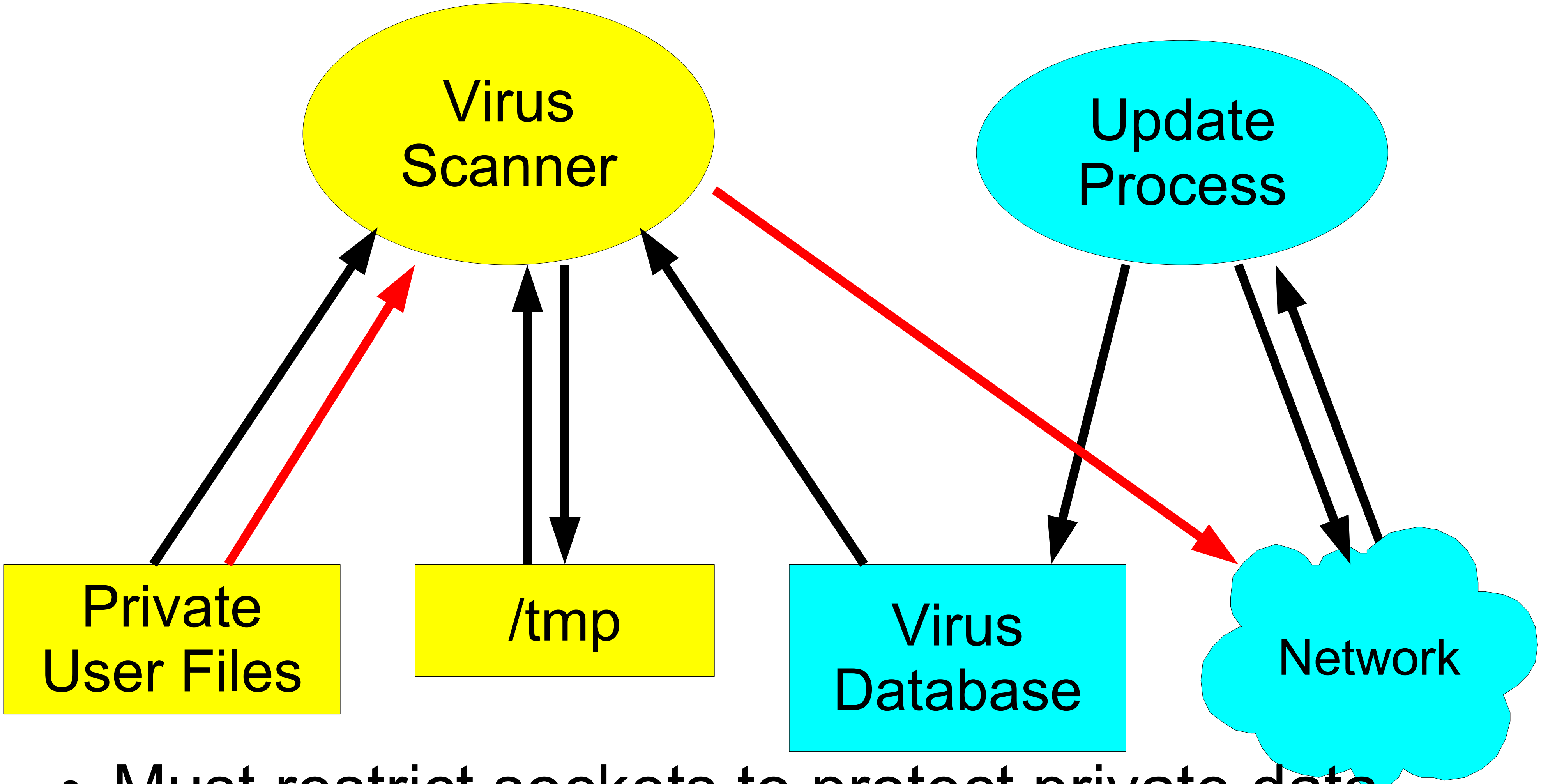


Information Flow Control

Goal: private files cannot go onto the network



Buggy scanner leaks private data



Virus Scanner

Update Process

Private User Files

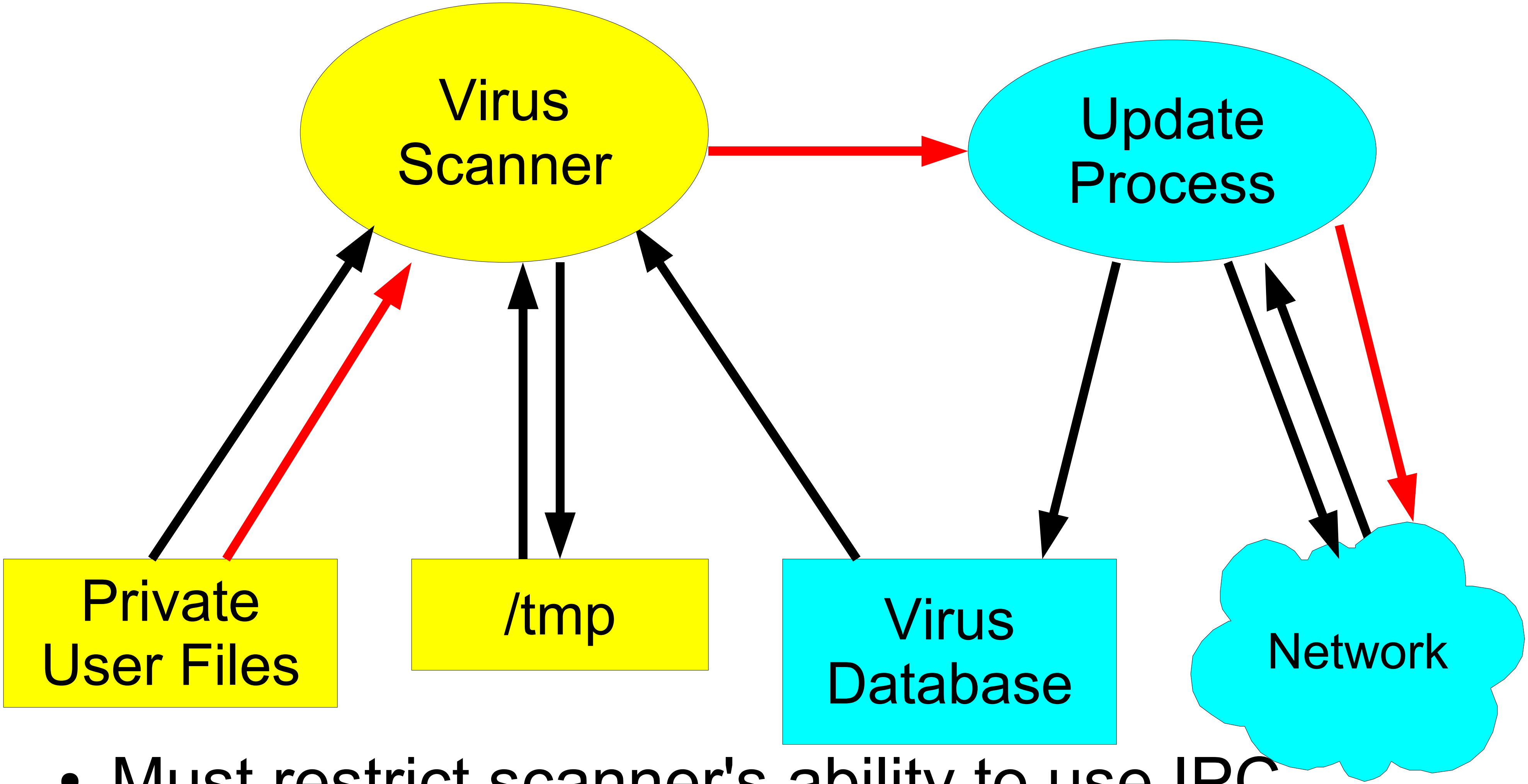
/tmp

Virus Database

Network

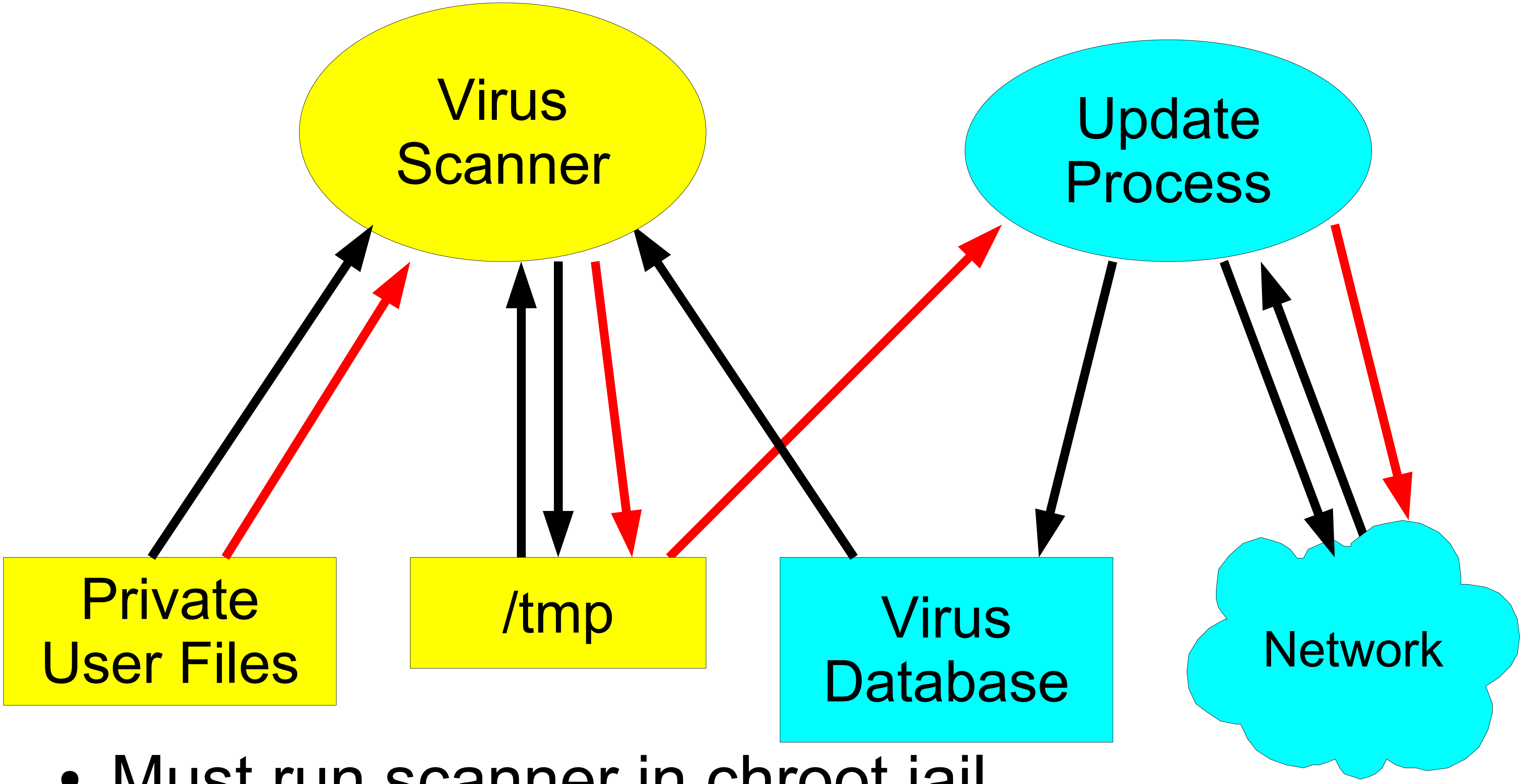
- Must restrict sockets to protect private data

Buggy scanner leaks private data



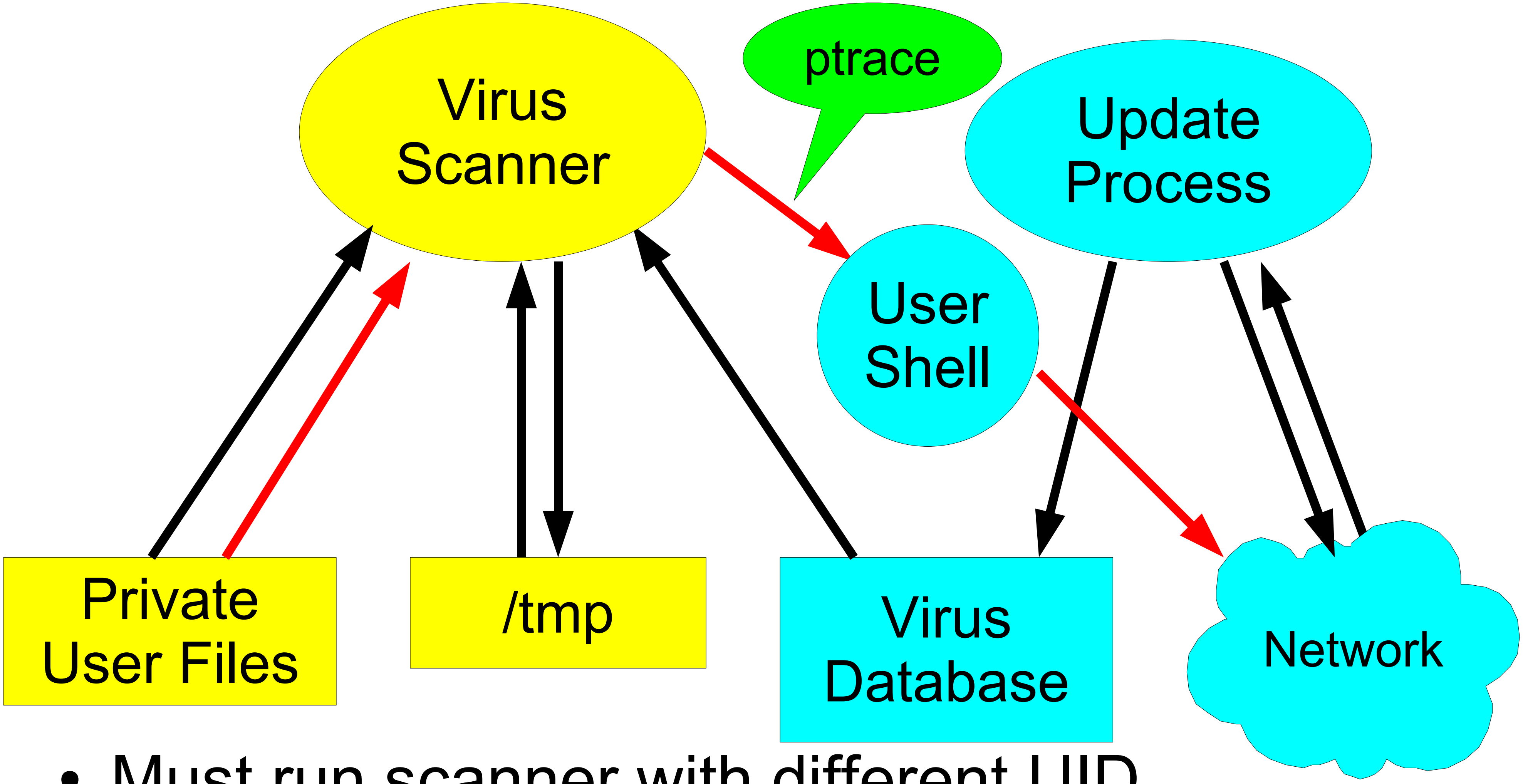
- Must restrict scanner's ability to use IPC

Buggy scanner leaks private data



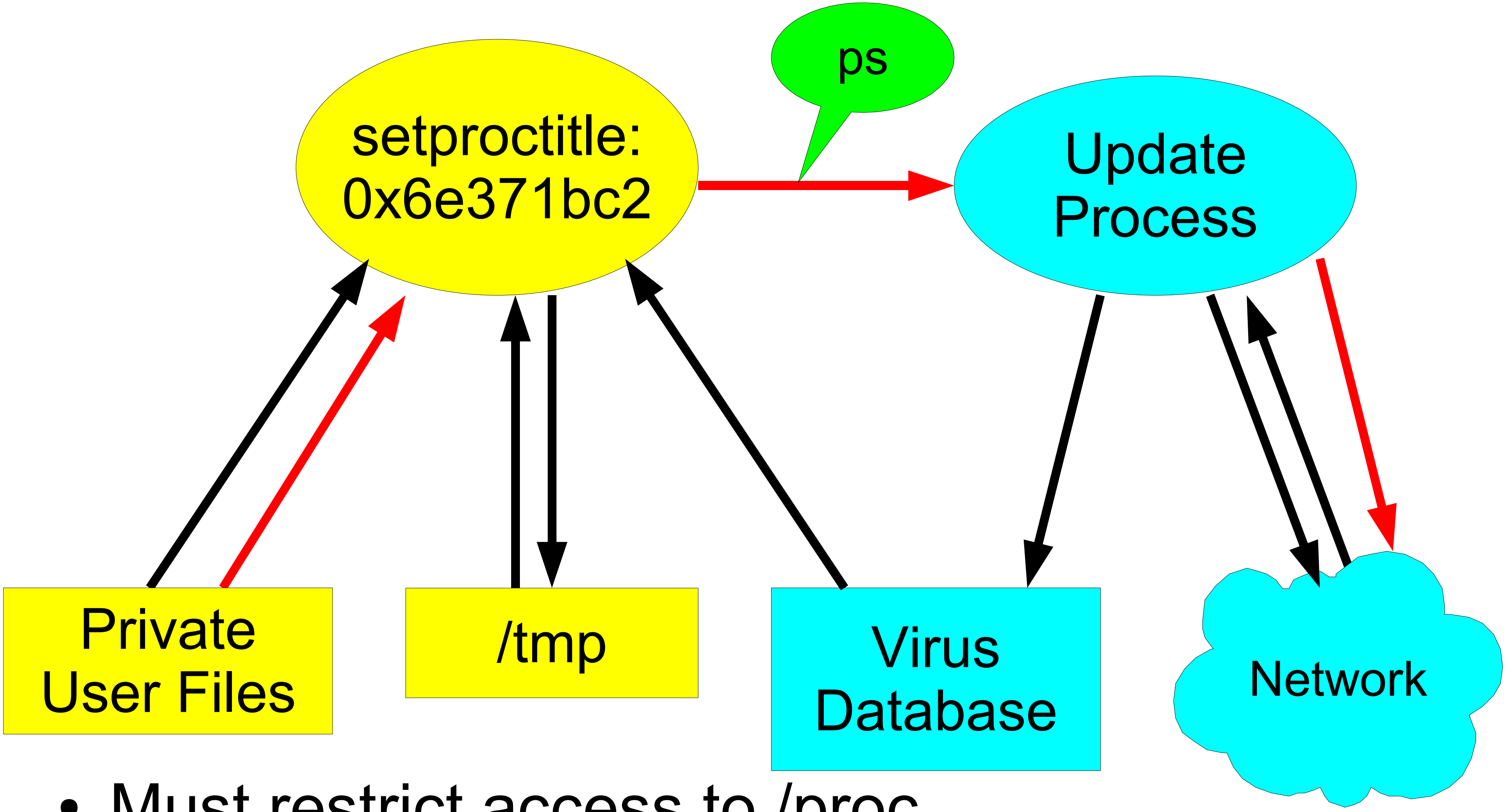
- Must run scanner in chroot jail

Buggy scanner leaks private data



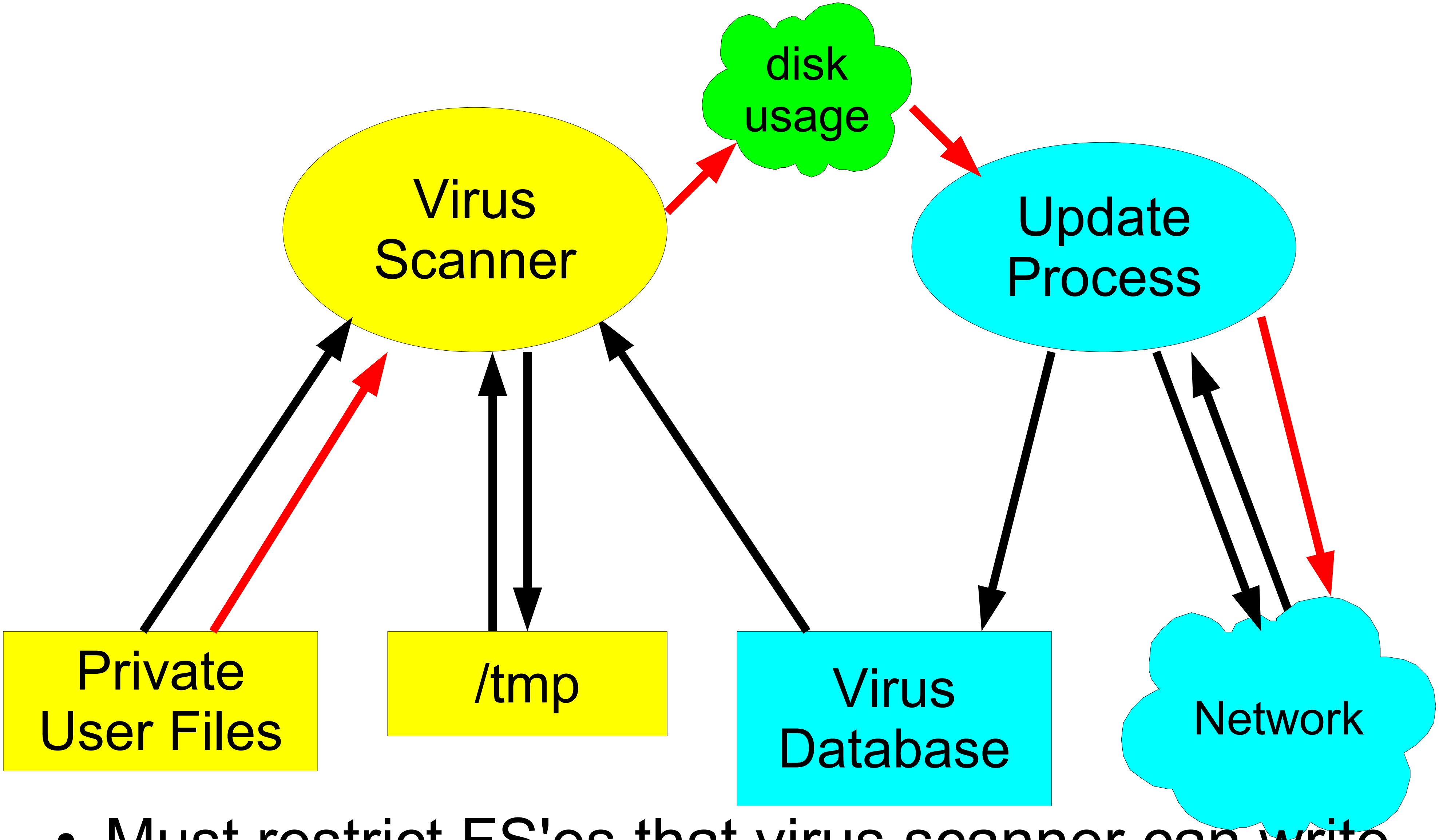
- Must run scanner with different UID

Buggy scanner leaks private data



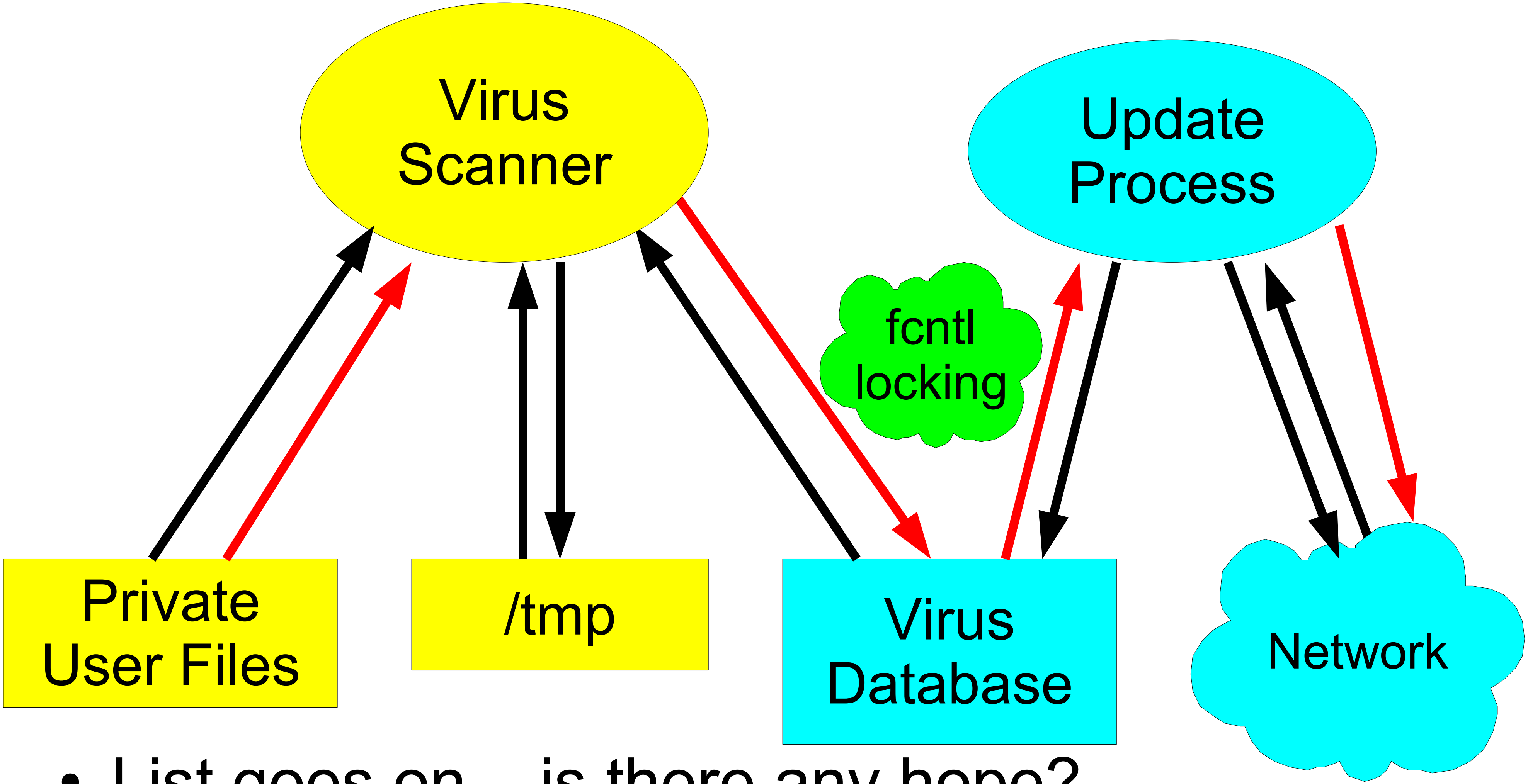
- Must restrict access to /proc, ...

Buggy scanner leaks private data



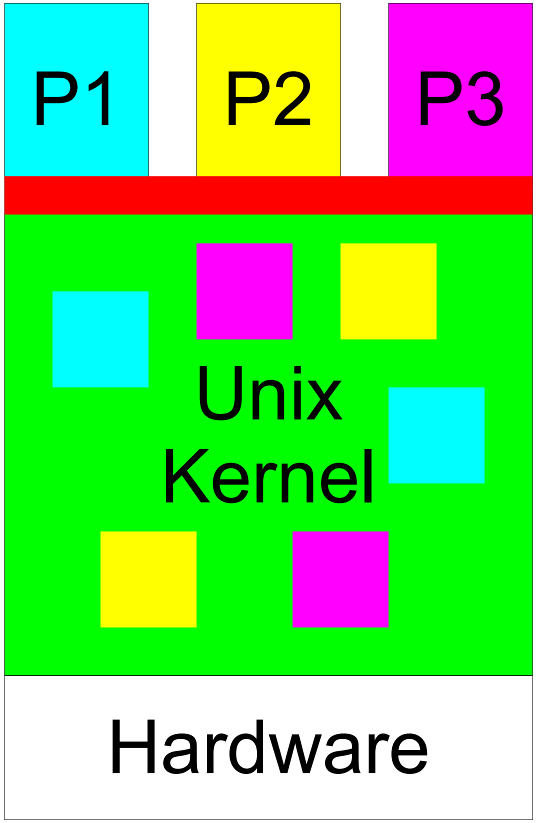
- Must restrict FS'es that virus scanner can write

Buggy scanner leaks private data



- List goes on – is there any hope?

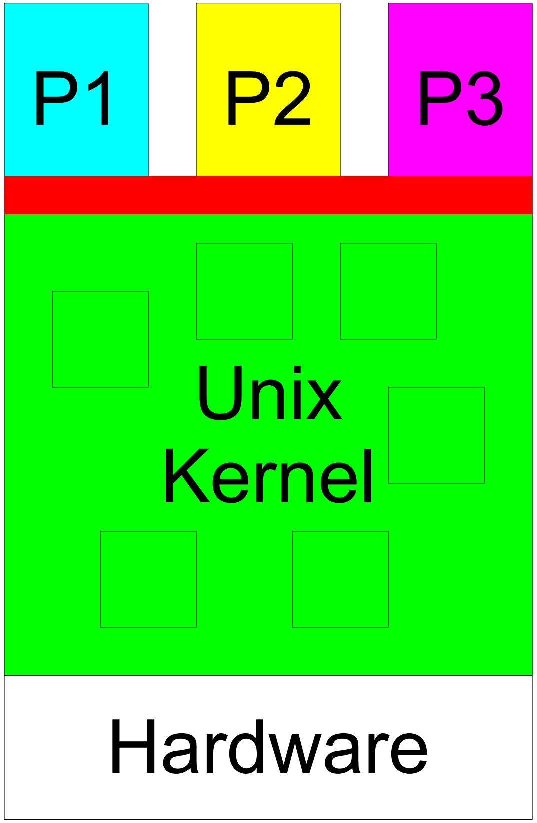
What's going on?



Unix

- Kernel not designed to control information flow
- Retrofitting difficult
  - Need to track potentially any memory observed or modified by a system call!
  - Hard to even enumerate

What's going on?

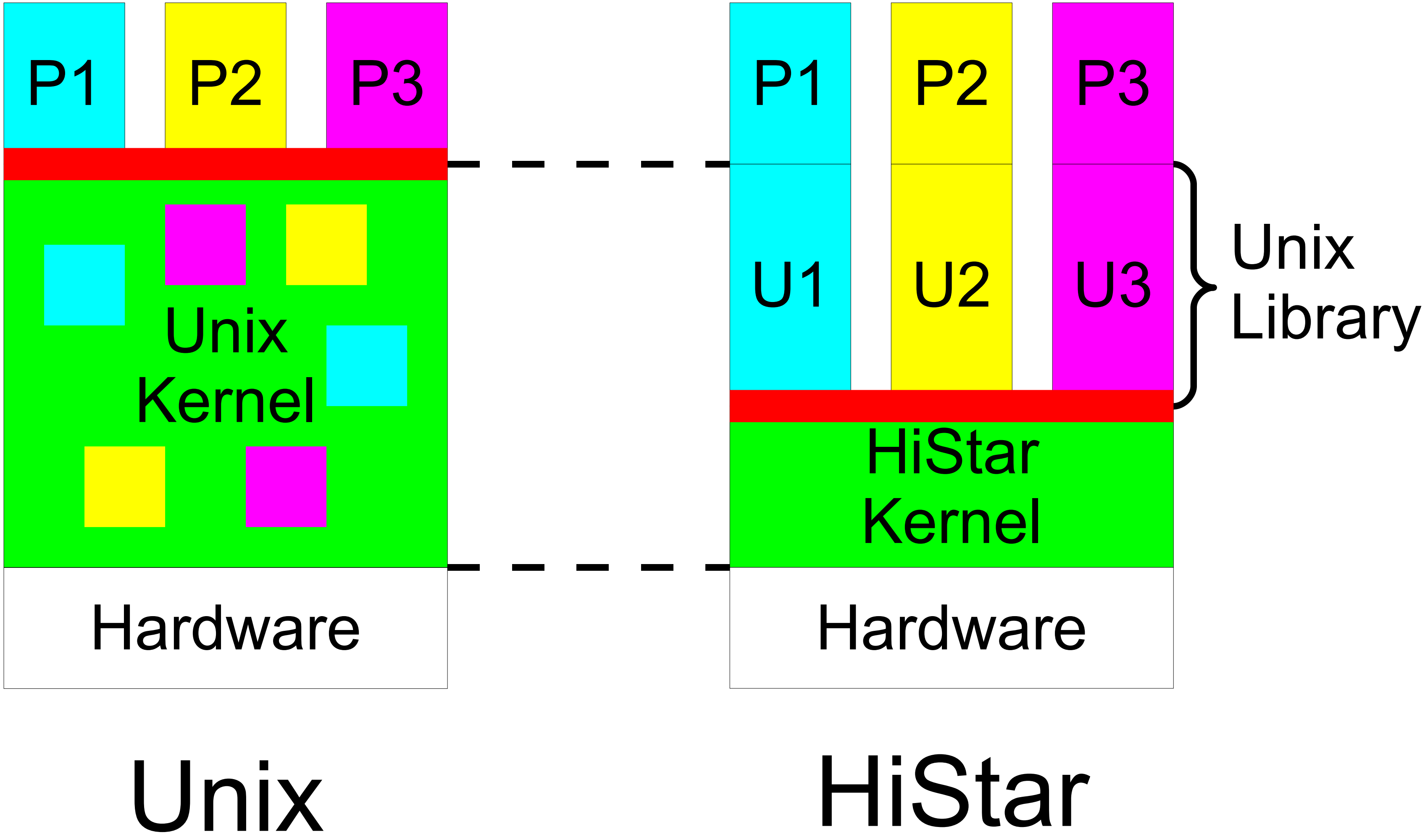


Unix

- Kernel not designed to control information flow
- Retrofitting difficult
  - Need to track potentially any memory observed or modified by a system call!
  - Hard to even enumerate

HiStar Solution

- Make all state explicit, track all communication

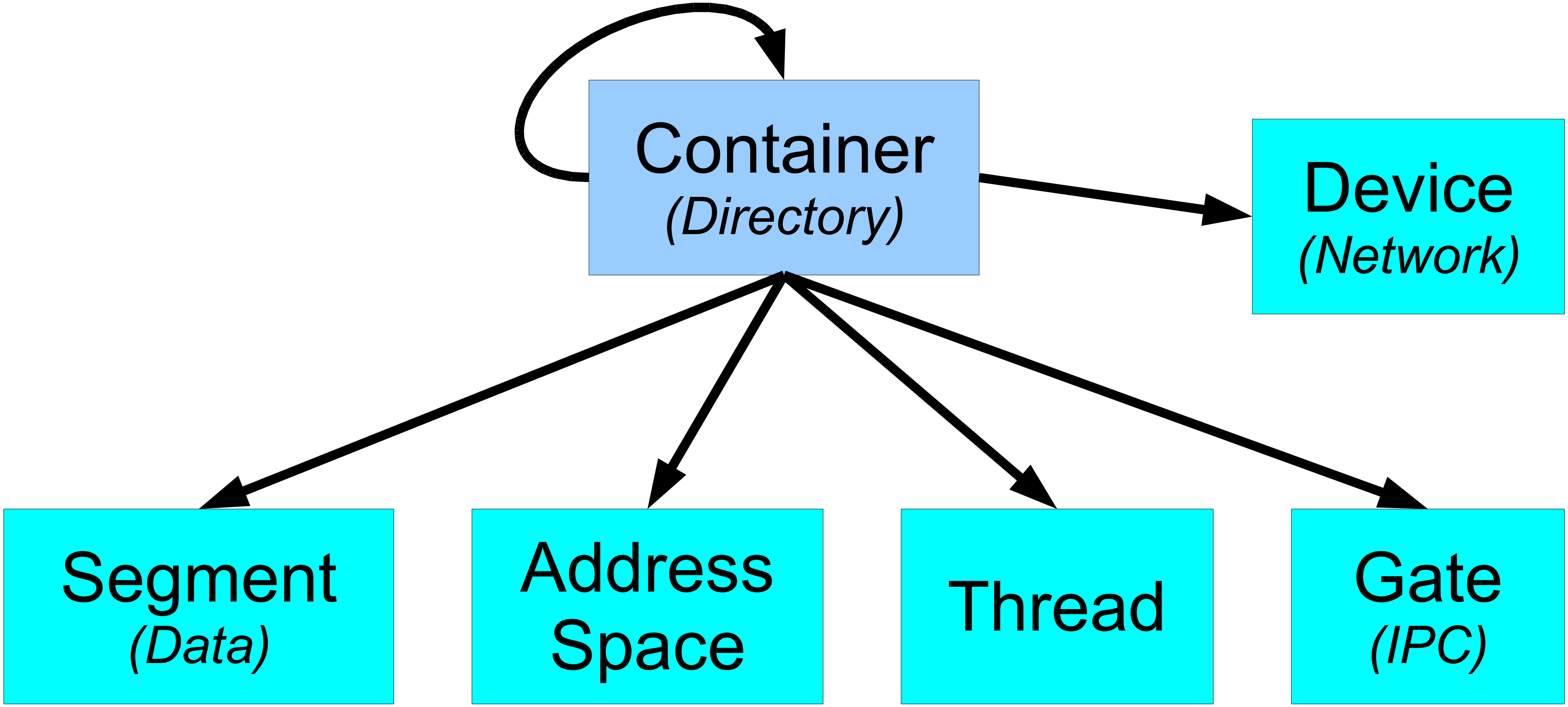


HiStar: Contributions

- Narrow kernel interface, few comm. channels
  - Minimal mechanism: enough for a Unix library
  - Strong control over information flow
  - Overall theme: make everything explicit

- Unix support implemented as user-level library
  - Unix communication channels are made explicit, in terms of HiStar's mechanisms
  - Provides control over the gamut of Unix channels

HiStar kernel objects



Container
(Directory)

Device
(Network)

Segment
(Data)

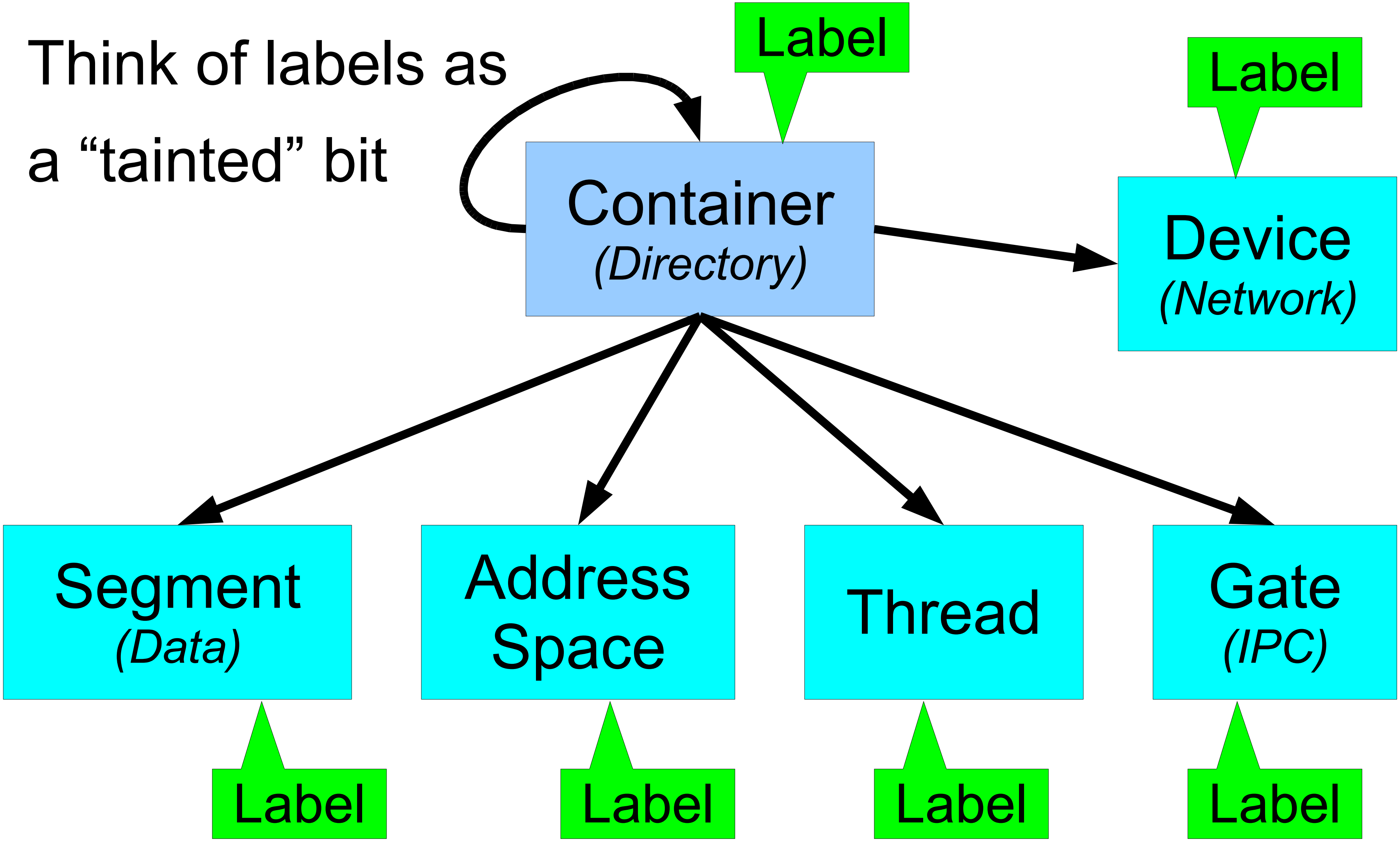
Address Space

Thread

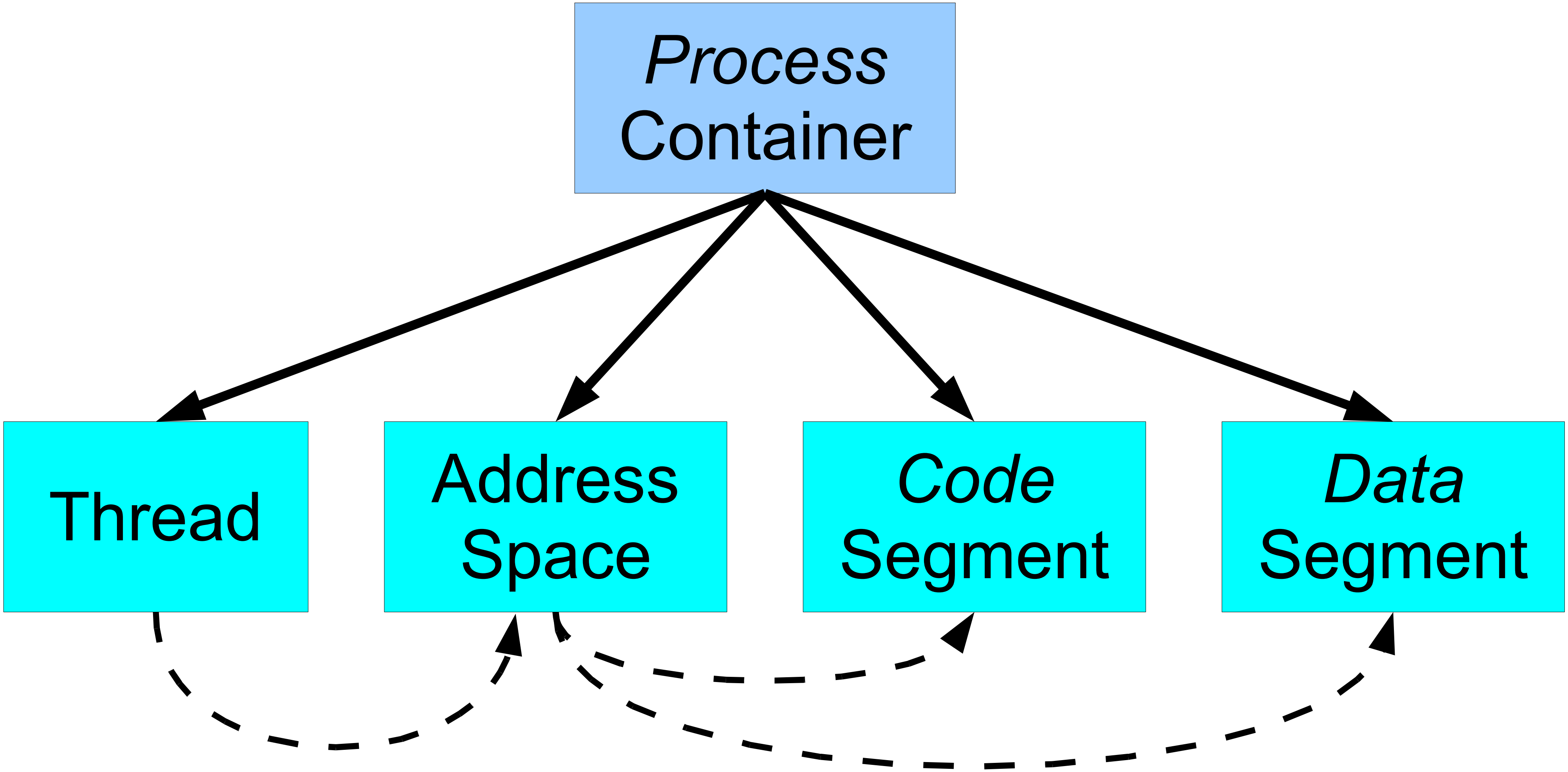
Gate
(IPC)

HiStar kernel objects

Think of labels as
a “tainted” bit



HiStar: Unix process



Process Container

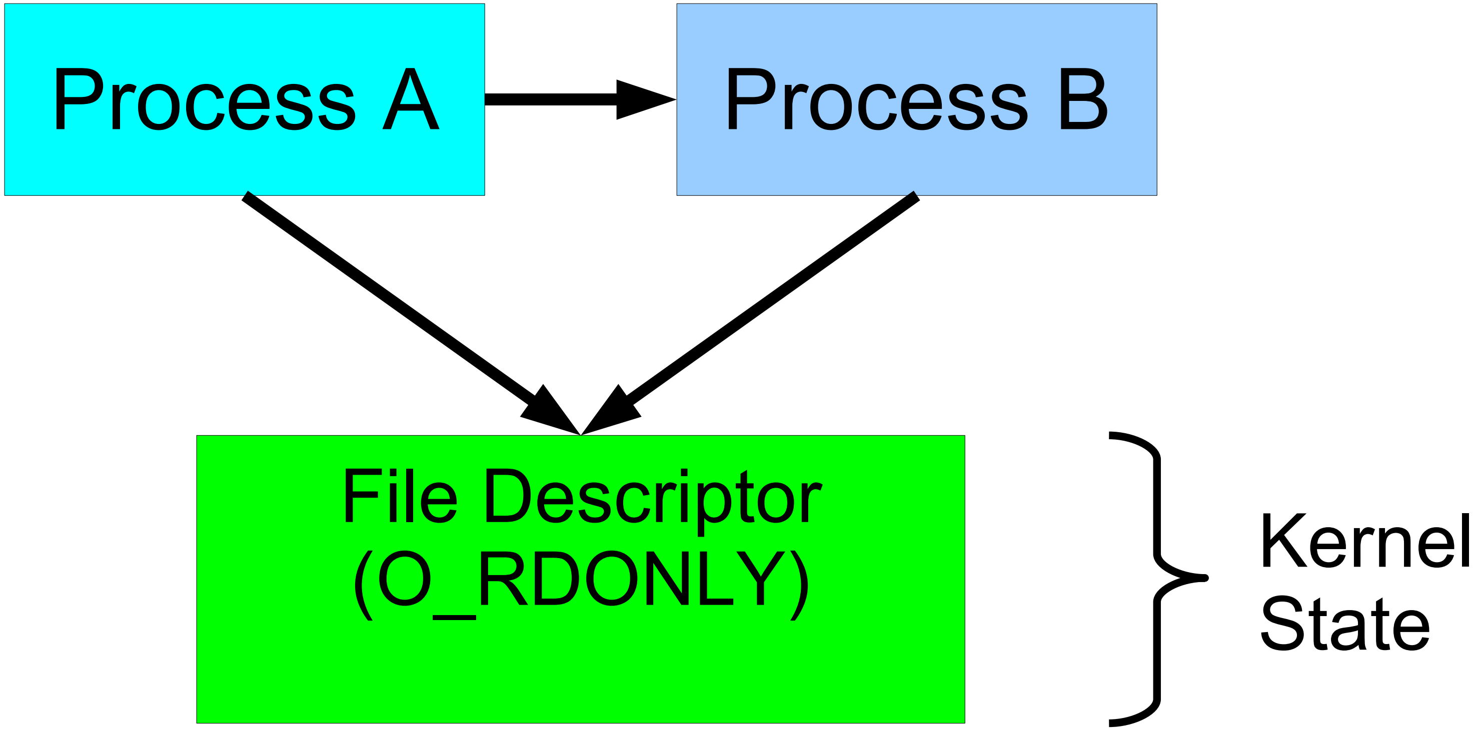
Thread

Address Space

Code Segment

Data Segment

Unix File Descriptors



Process A

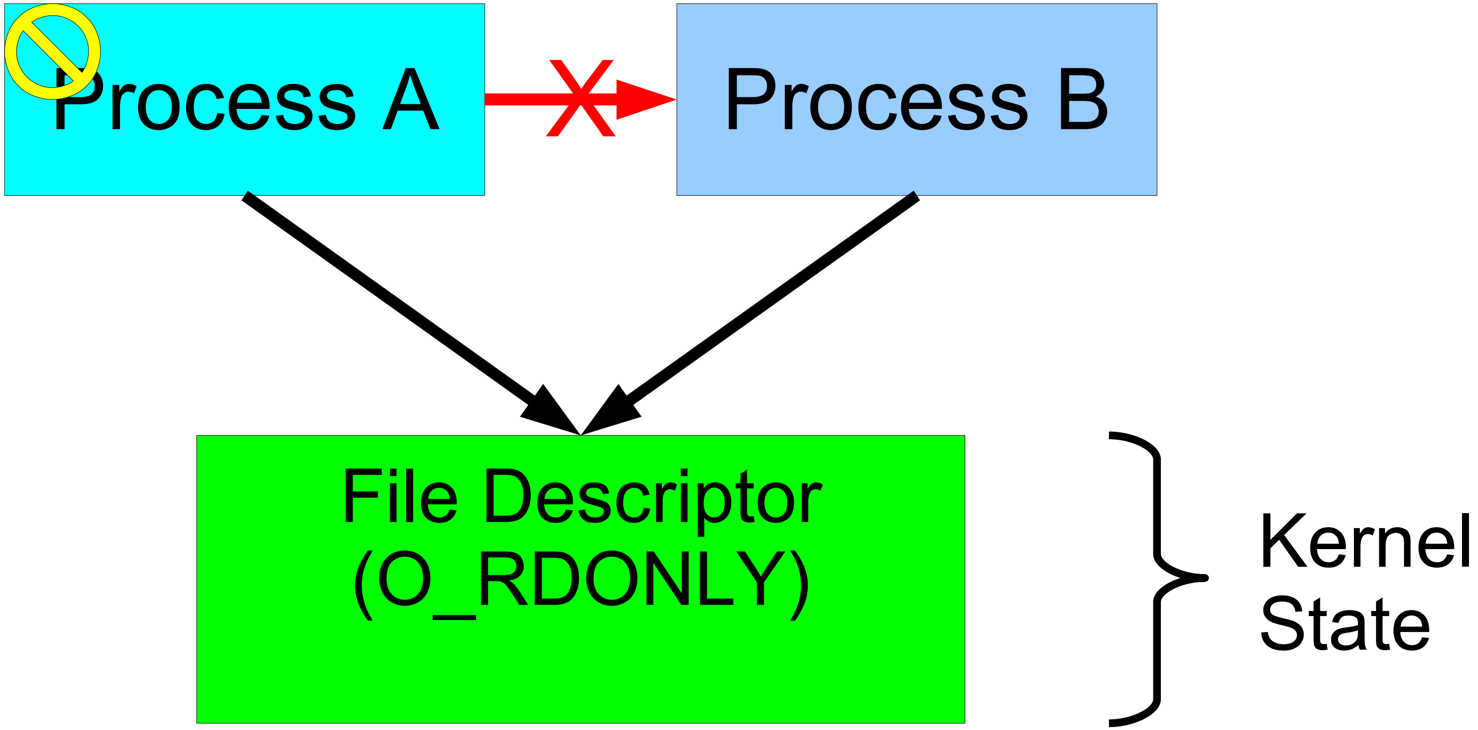
Process B

File Descriptor
(O_RDONLY)

Kernel
State

Unix File Descriptors

- Tainted process only talks to other tainted procs



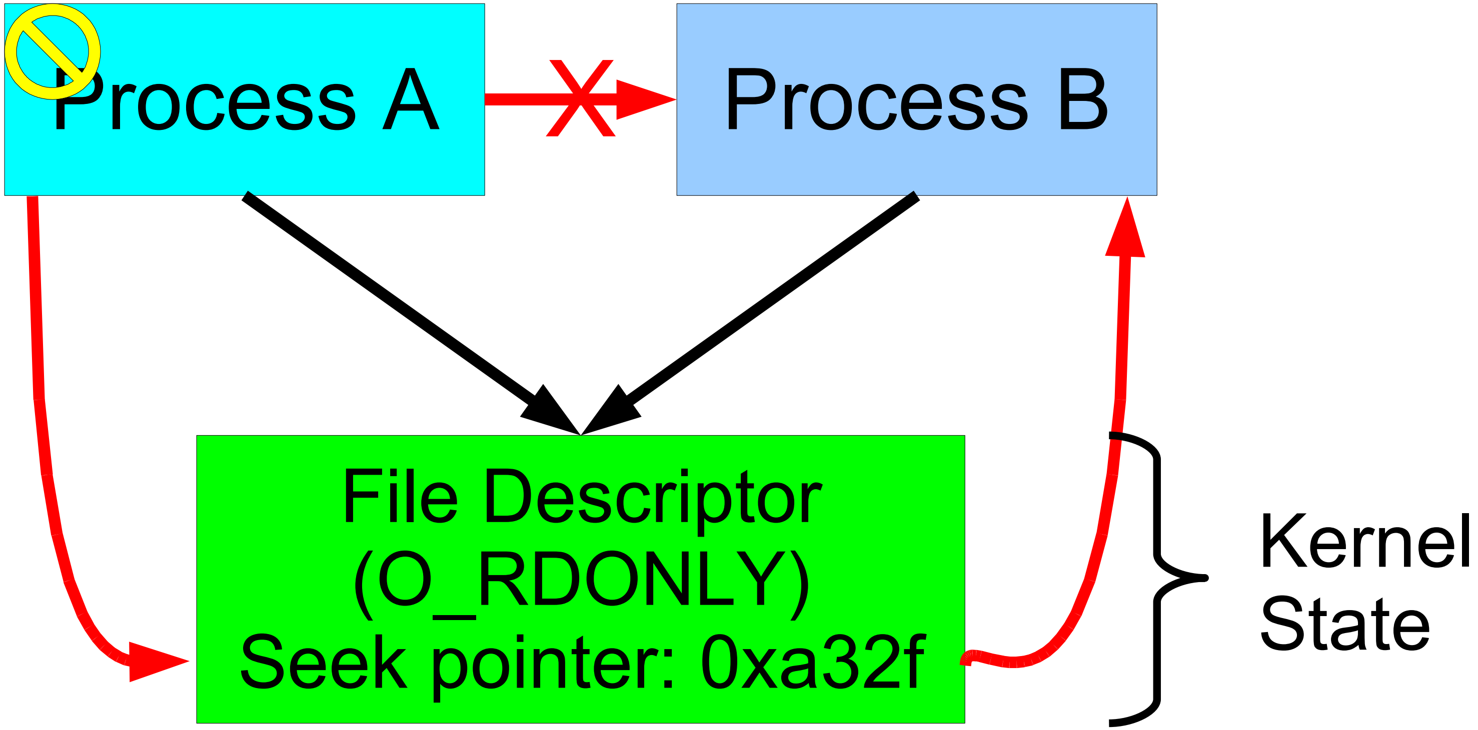
Process A

Process B

File Descriptor (O_RDONLY)

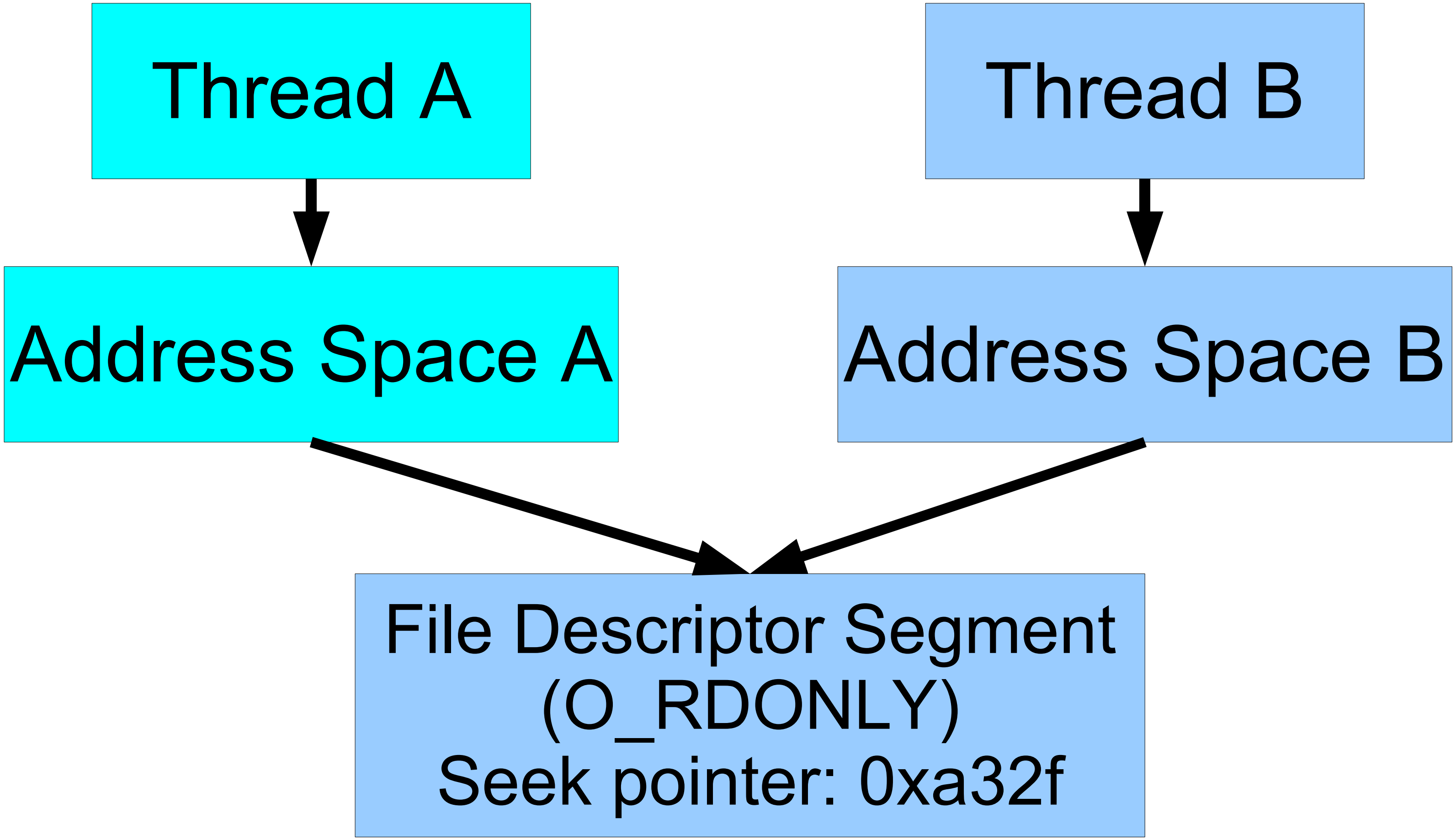
Kernel State

Unix File Descriptors



- Lots of shared state in kernel, easy to miss

HiStar File Descriptors



Thread A

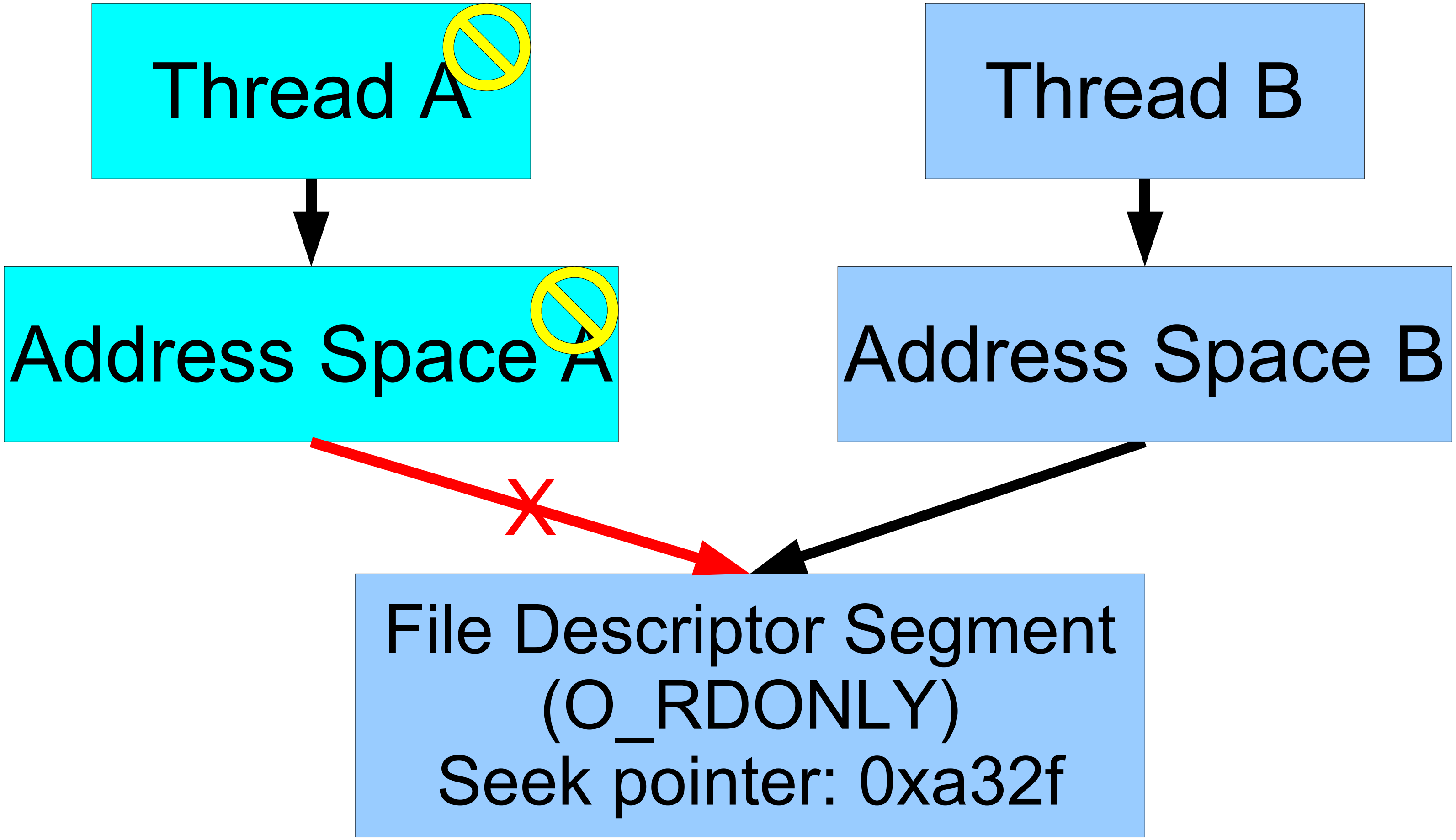
Thread B

Address Space A

Address Space B

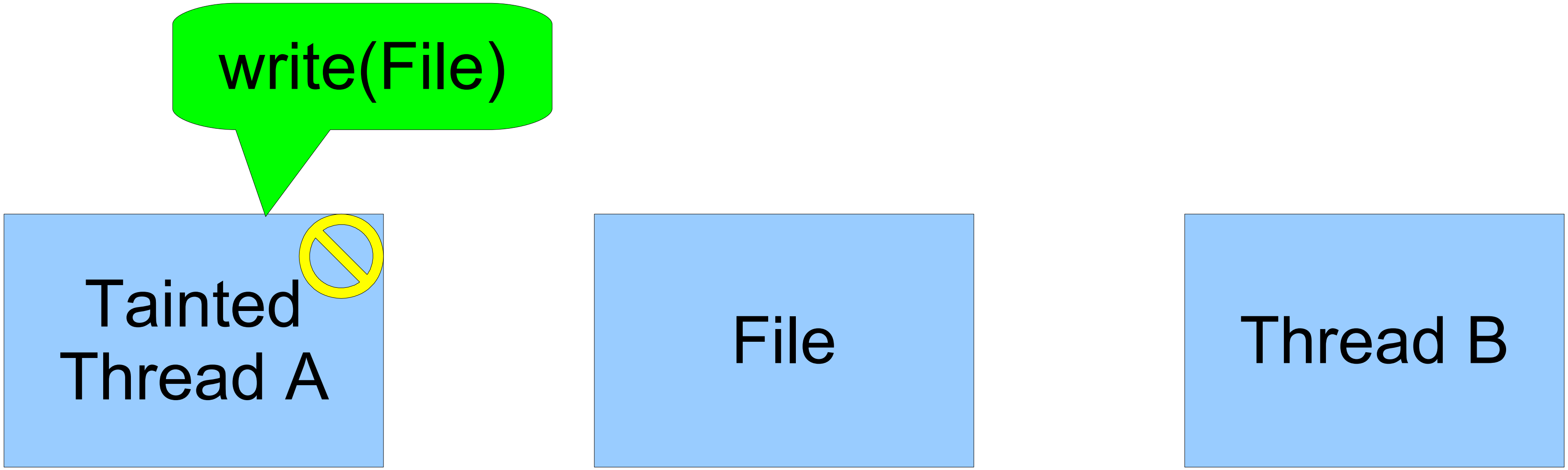
File Descriptor Segment
(O_RDONLY)
Seek pointer: 0xa32f

HiStar File Descriptors



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

Taint Tracking Strawman



write(File)

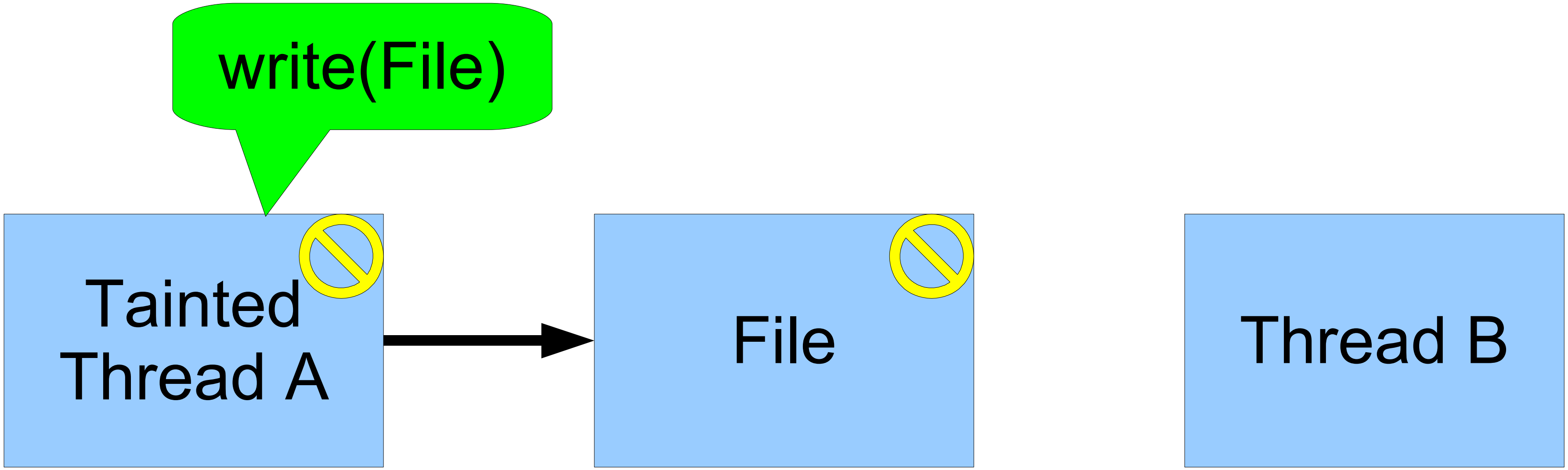
Tainted Thread A

File

Thread B

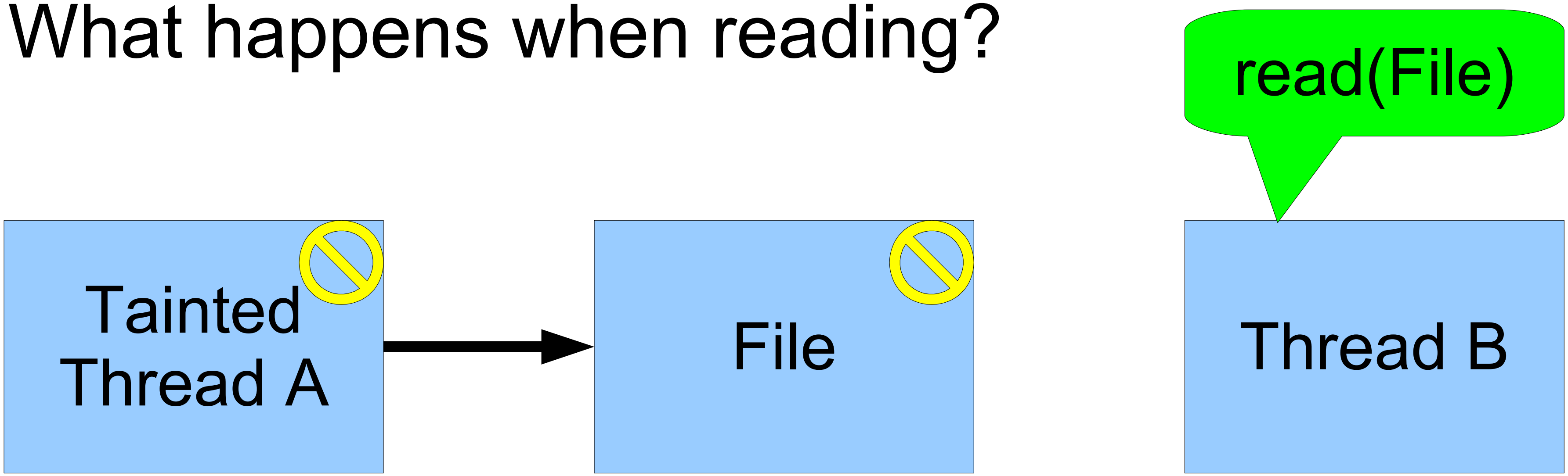
Taint Tracking Strawman

- Propagate taint when writing to file

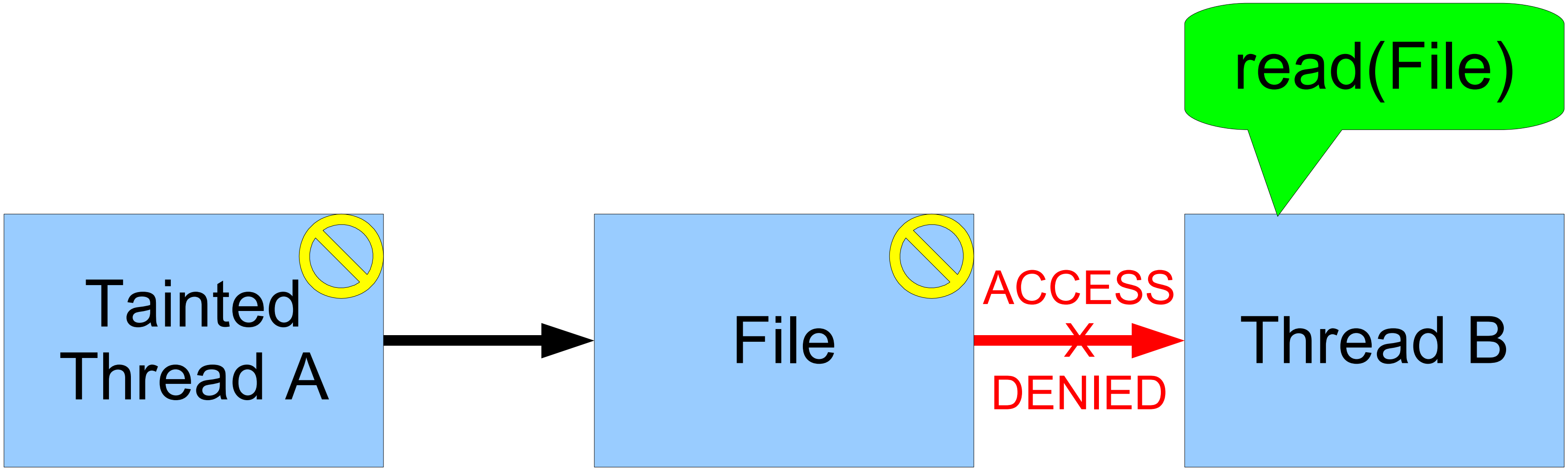


Taint Tracking Strawman

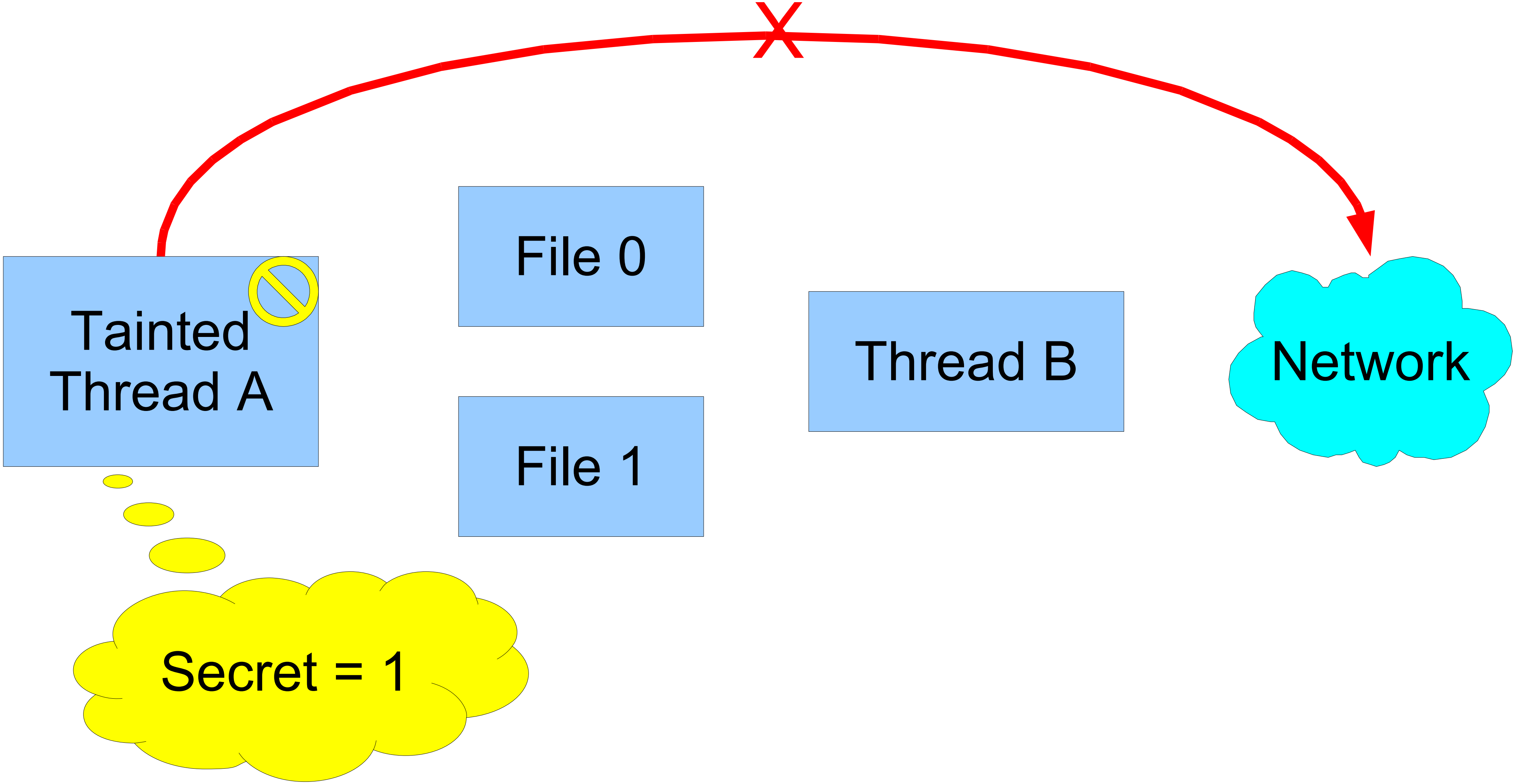
- Propagate taint when writing to file
- What happens when reading?



Taint Tracking Strawman



Strawman has Covert Channel



Tainted Thread A

File 0

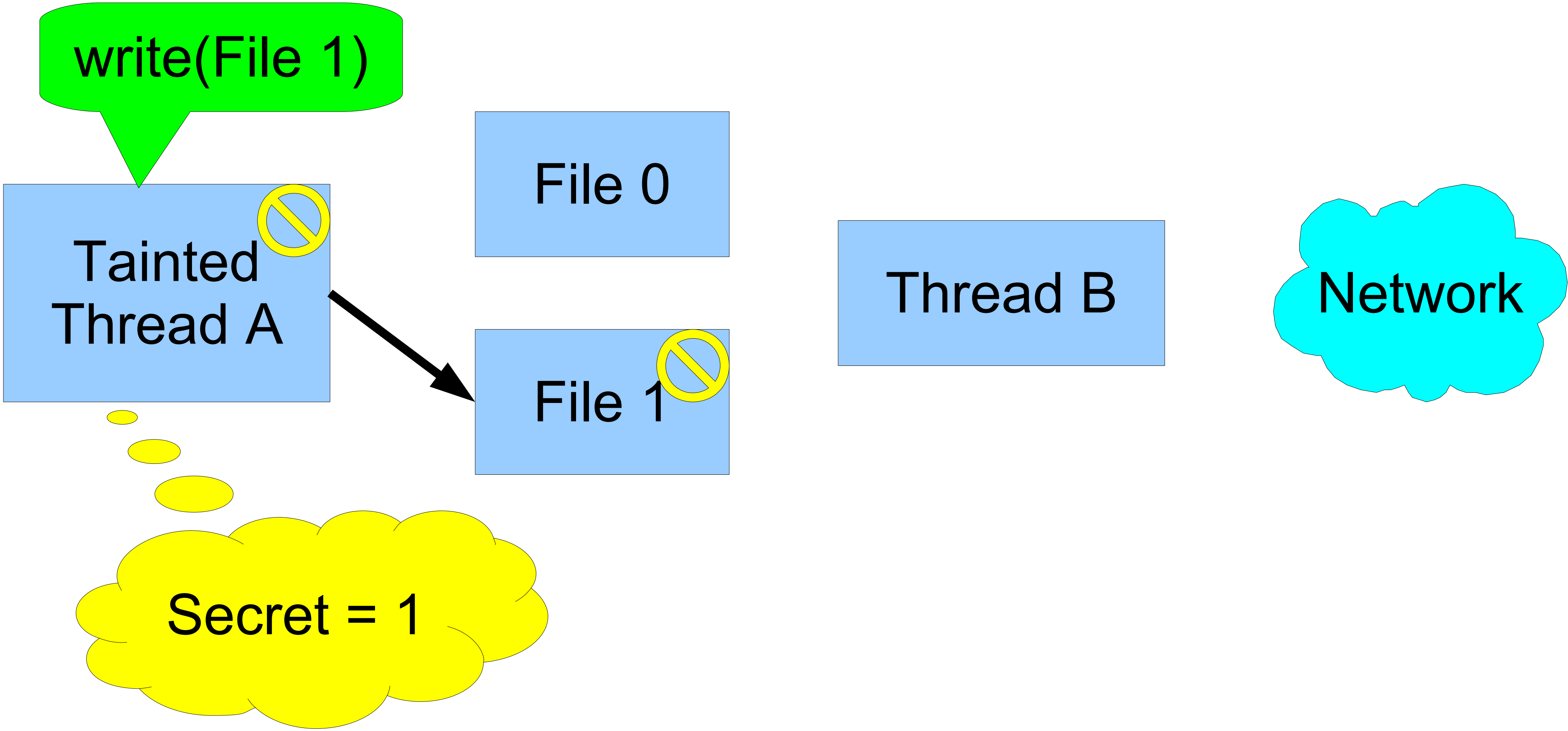
File 1

Thread B

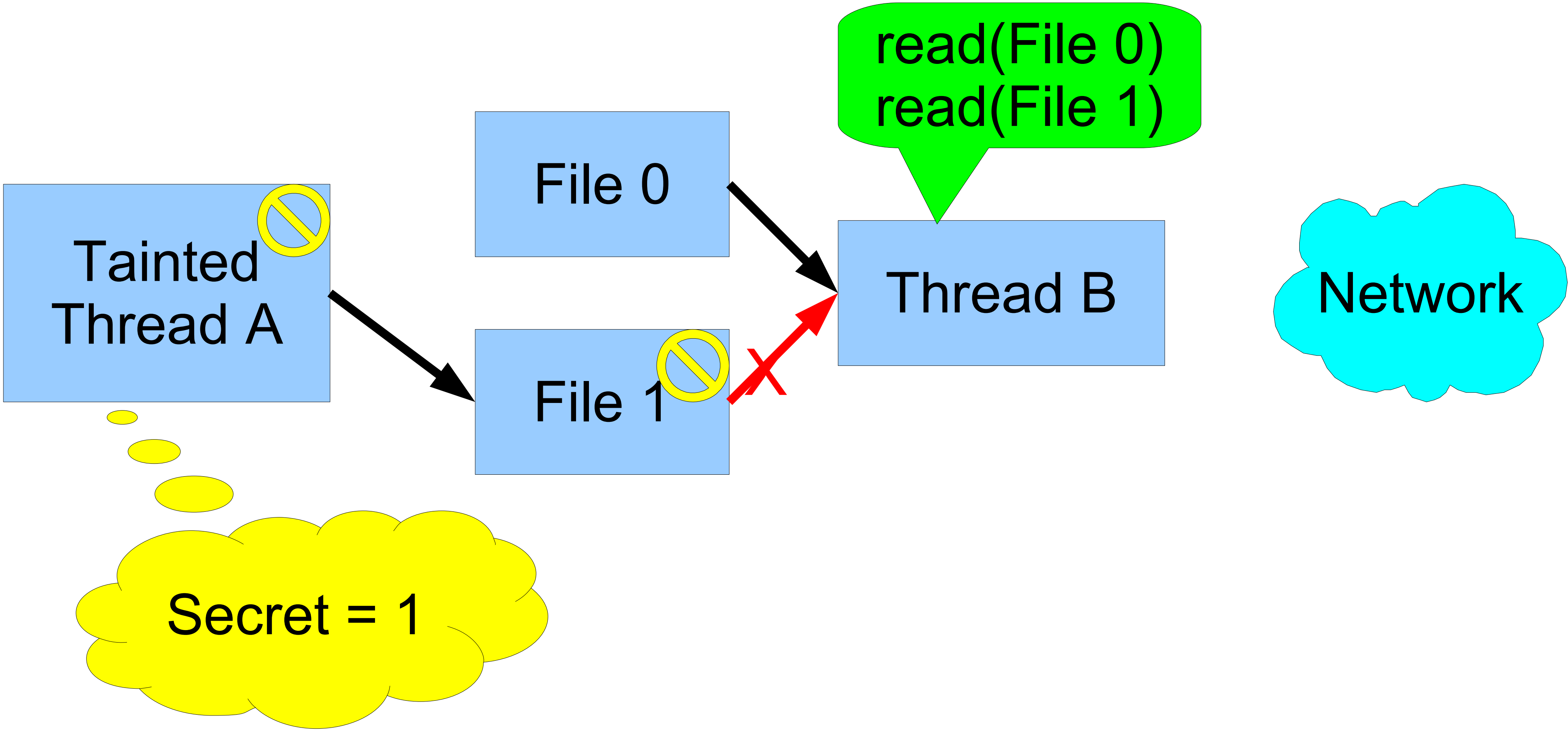
Network

Secret = 1

Strawman has Covert Channel



Strawman has Covert Channel



Tainted Thread A

File 0

File 1

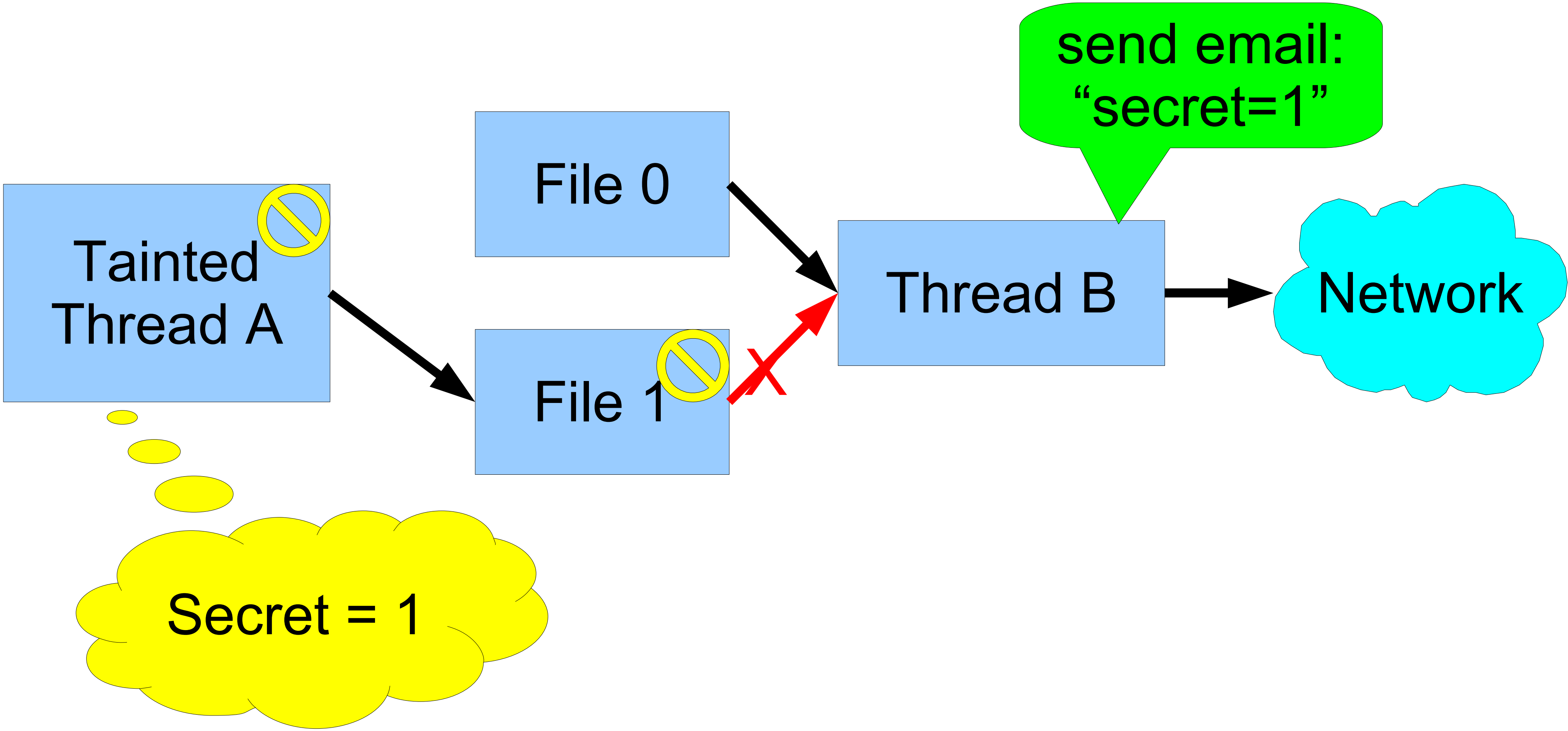
read(File 0)
read(File 1)

Thread B

Network

Secret = 1

Strawman has Covert Channel



Tainted Thread A

File 0

File 1

Thread B

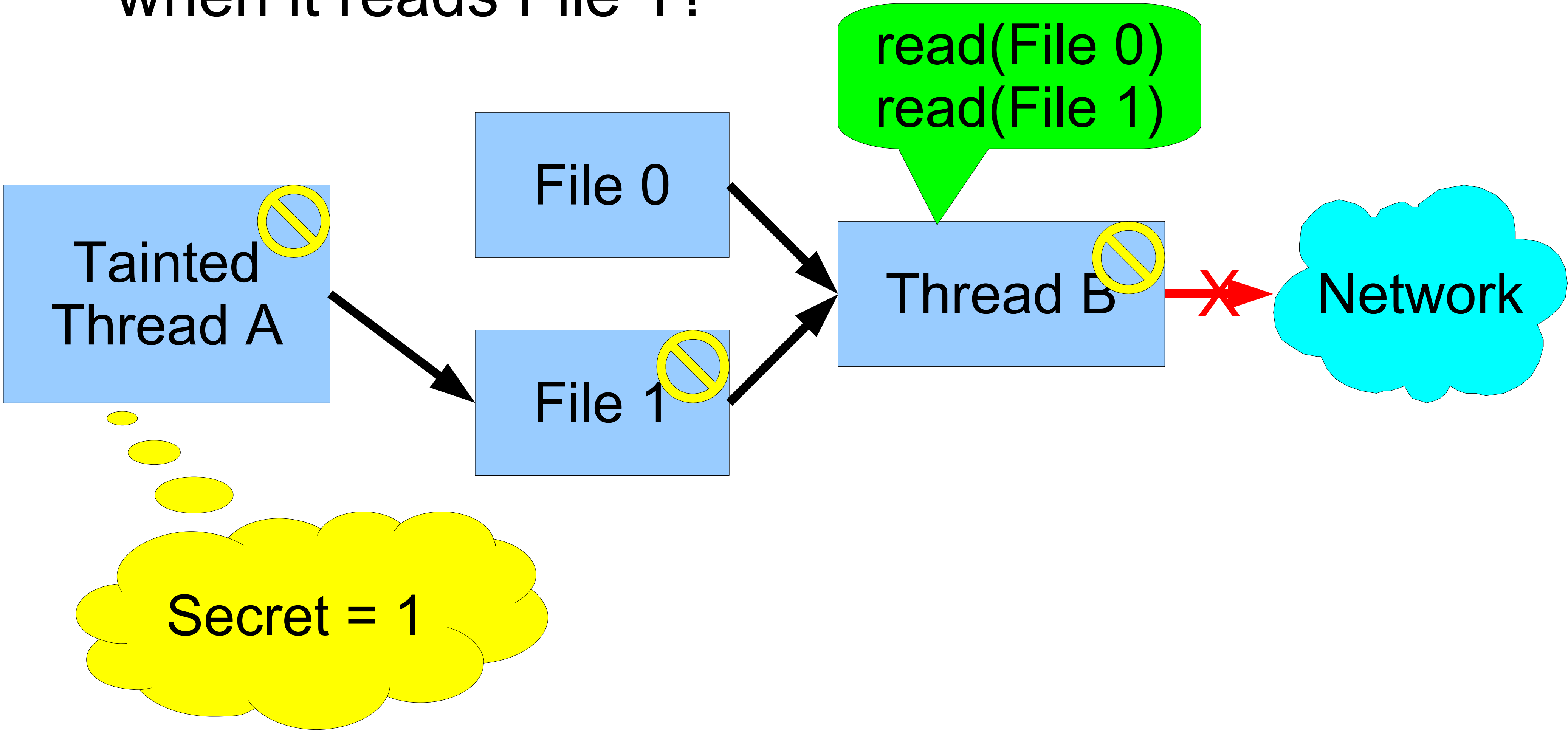
Network

send email: "secret=1"

Secret = 1

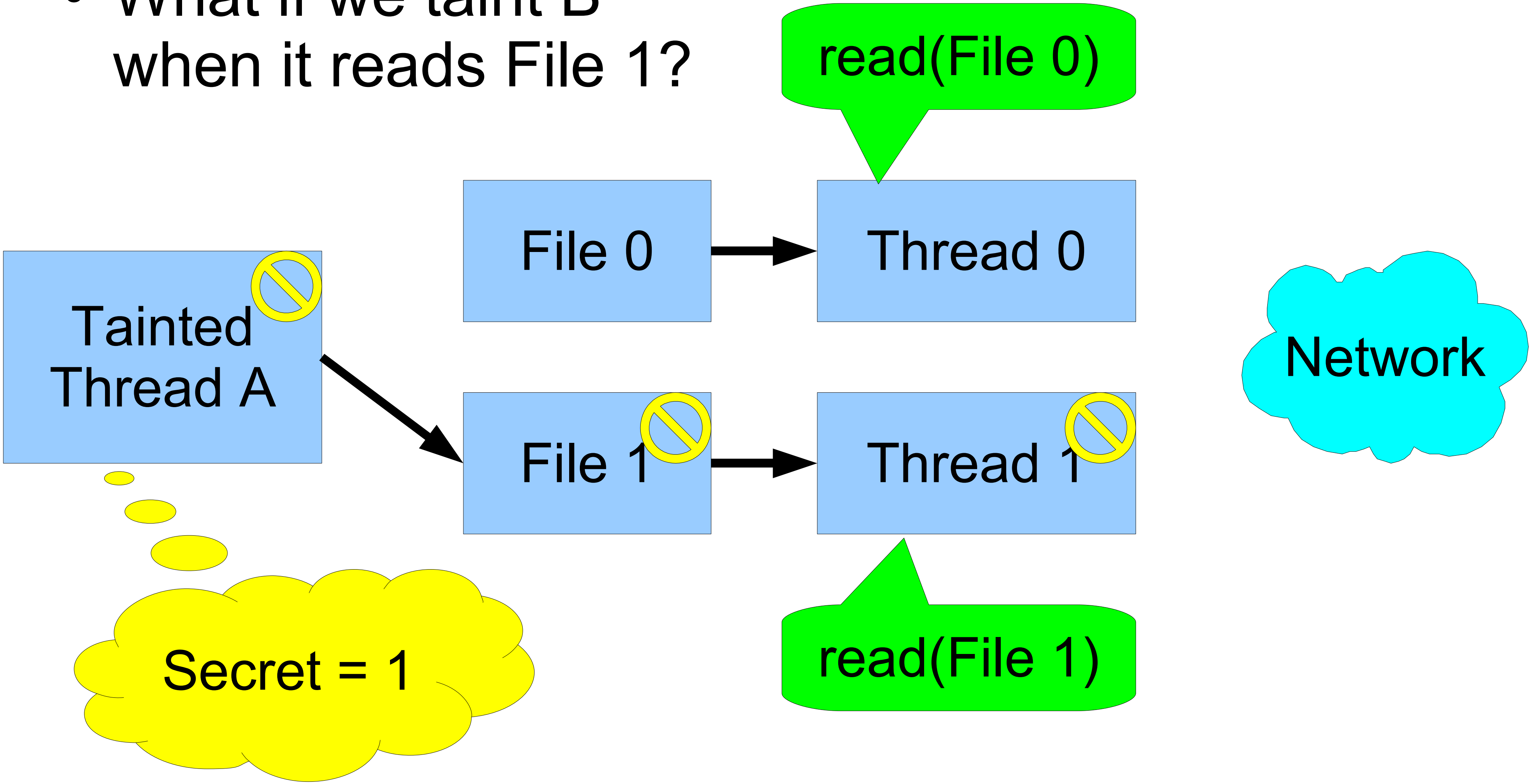
Strawman has Covert Channel

- What if we taint B when it reads File 1?



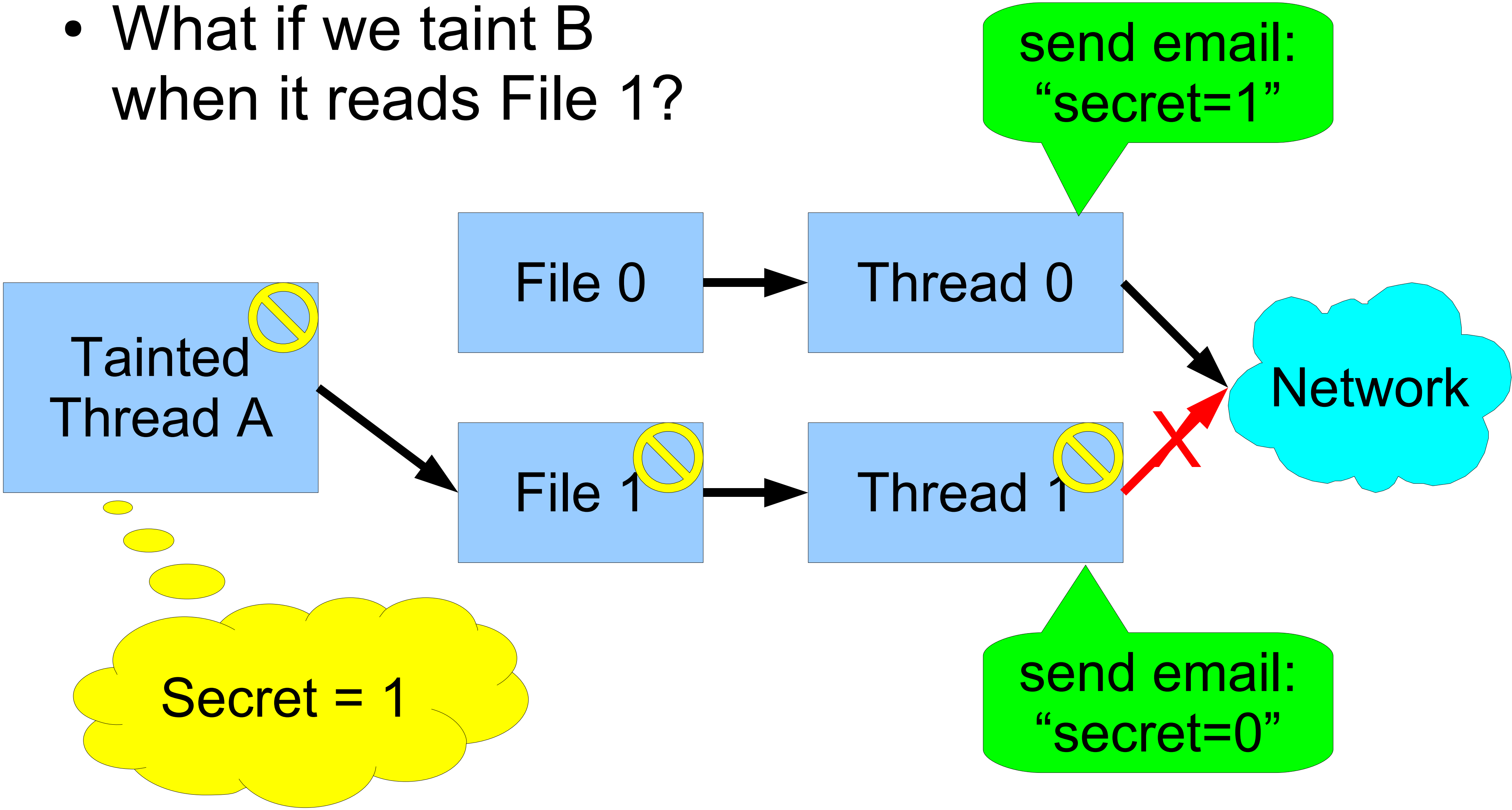
Strawman has Covert Channel

- What if we taint B when it reads File 1?



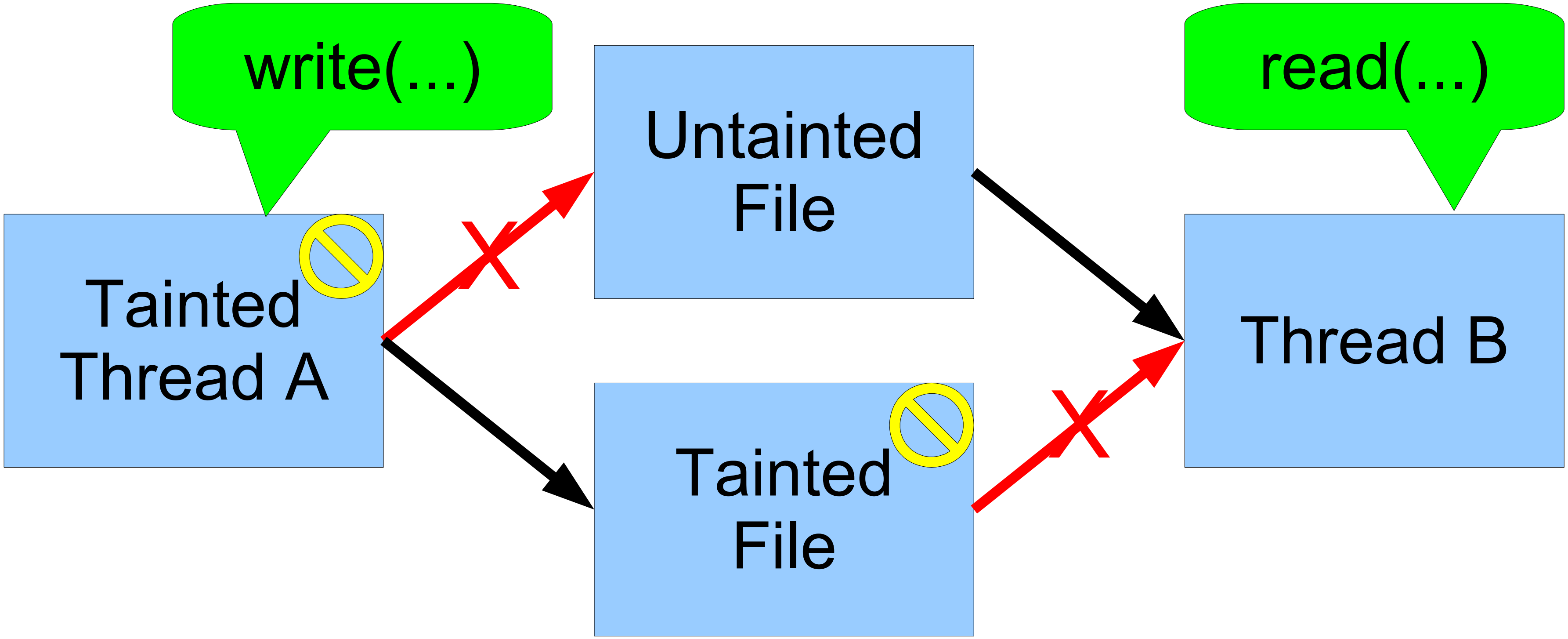
Strawman has Covert Channel

- What if we taint B when it reads File 1?



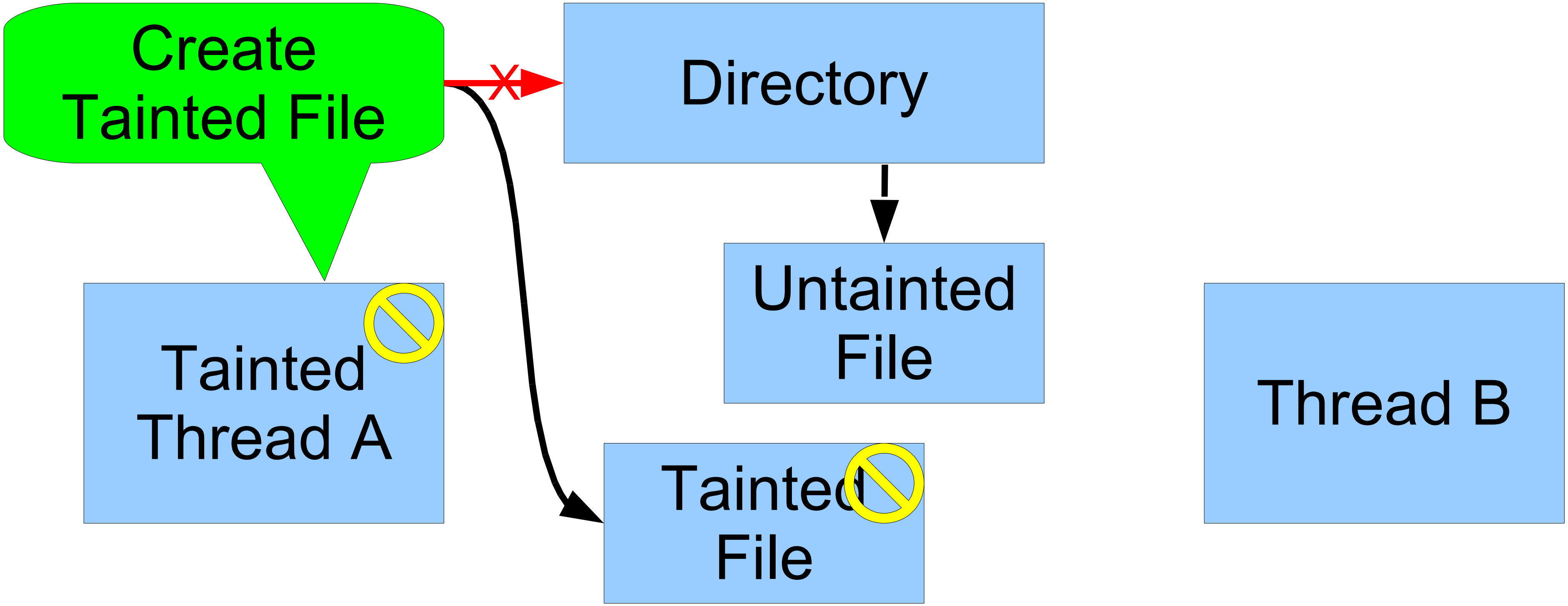
HiStar: Immutable File Labels

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



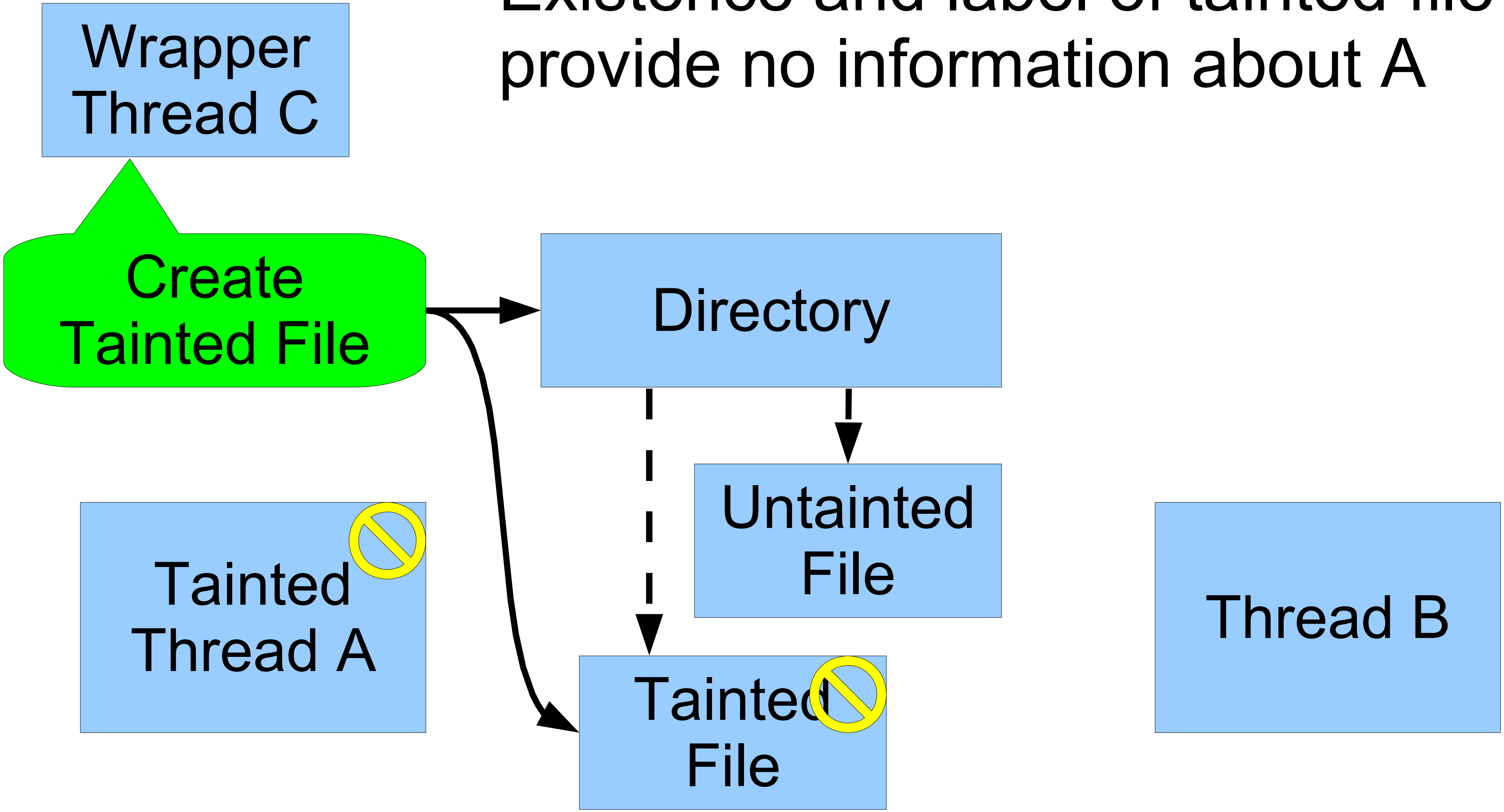
Who creates tainted files?

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



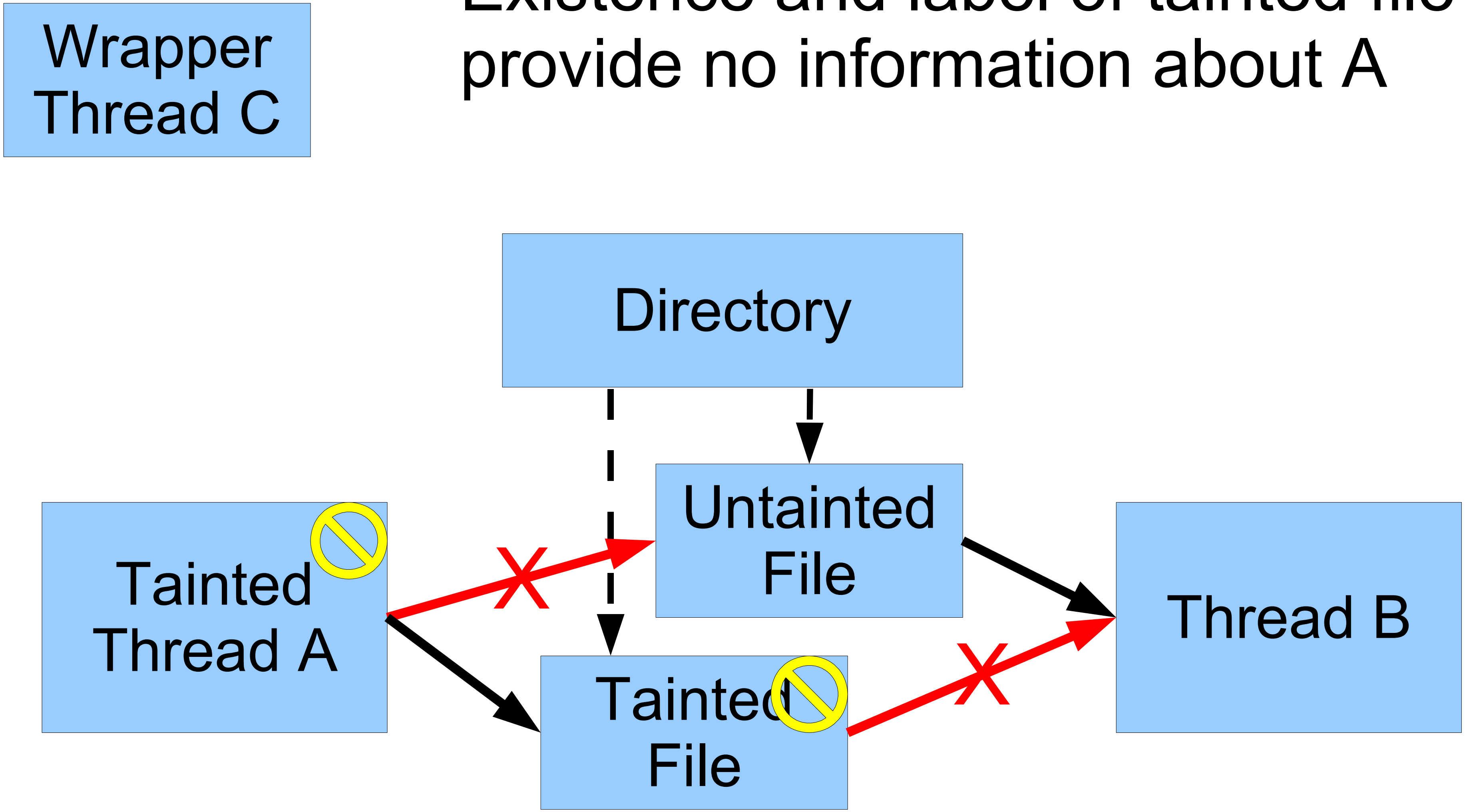
HiStar: Untainted thread pre-creates tainted file

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



Reading a tainted file

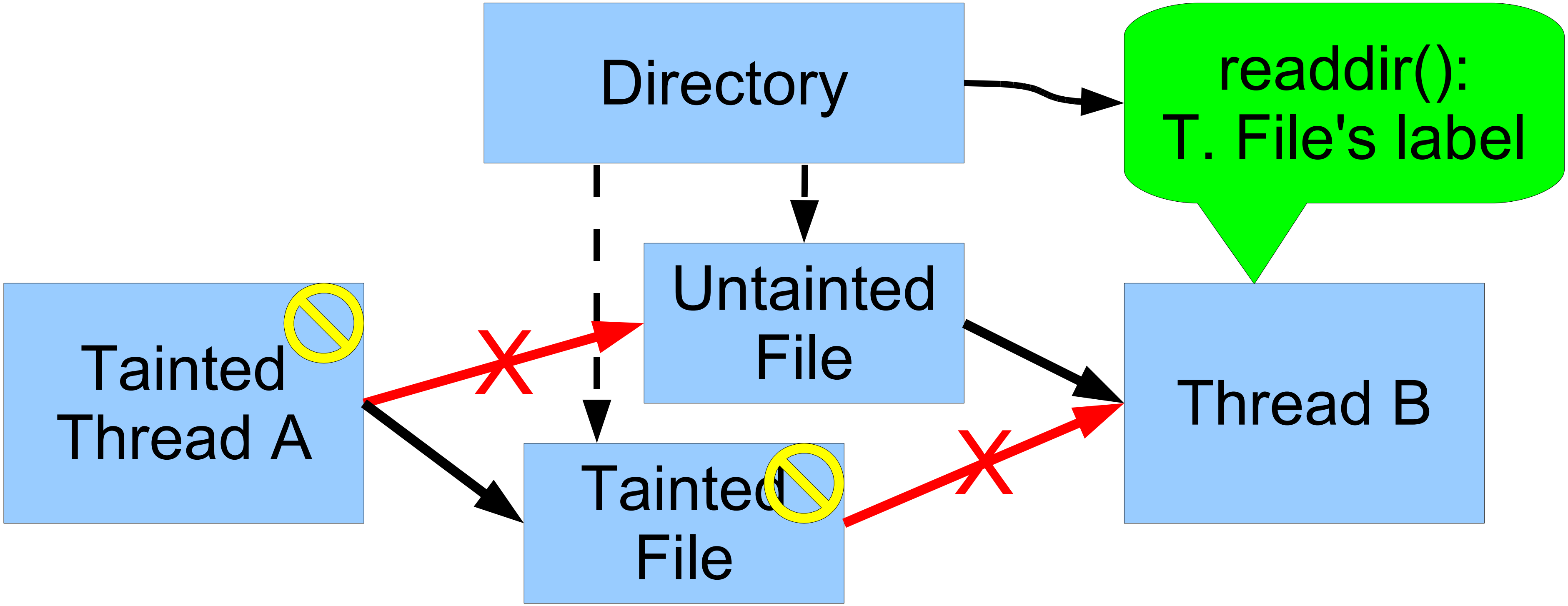
- Existence and label of tainted file provide no information about A



Reading a tainted file

Wrapper
Thread C

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



Directory

readdir():
T. File's label

Untainted
File

Tainted
Thread A

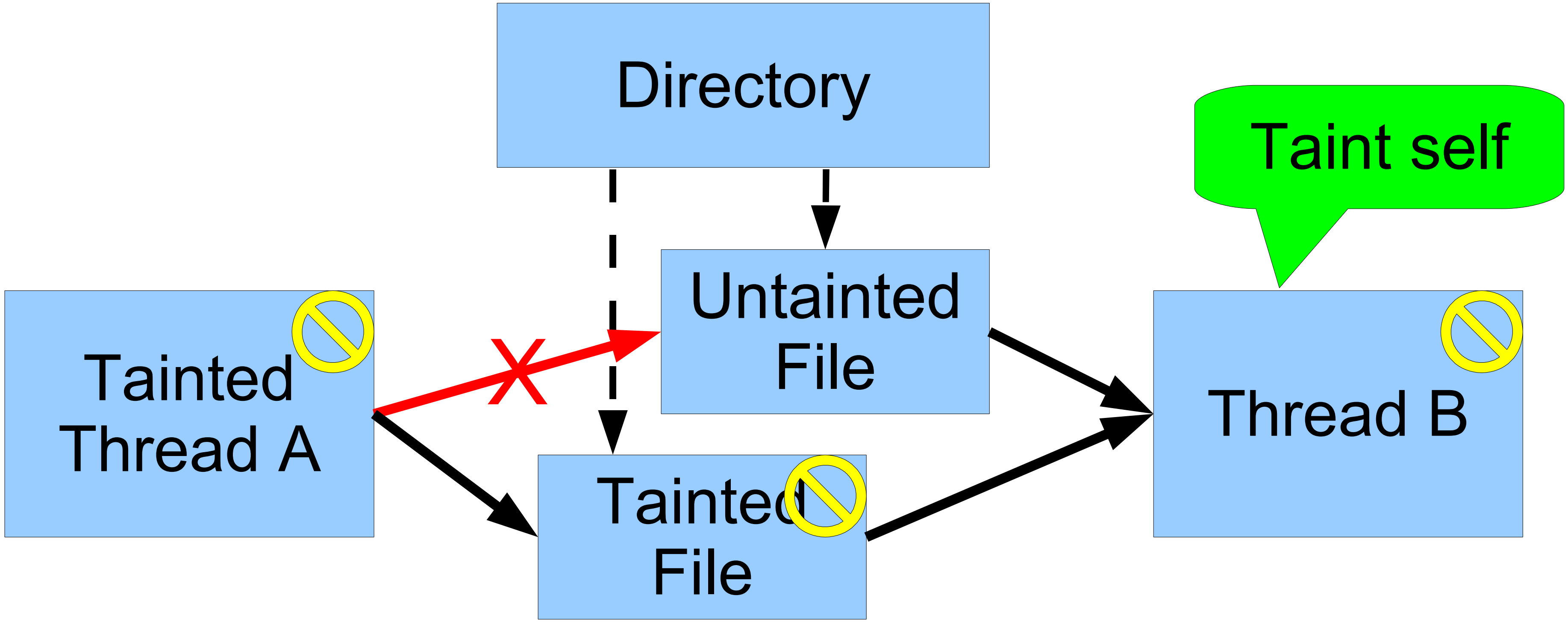
Thread B

Tainted
File

Reading a tainted file

Wrapper
Thread C

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

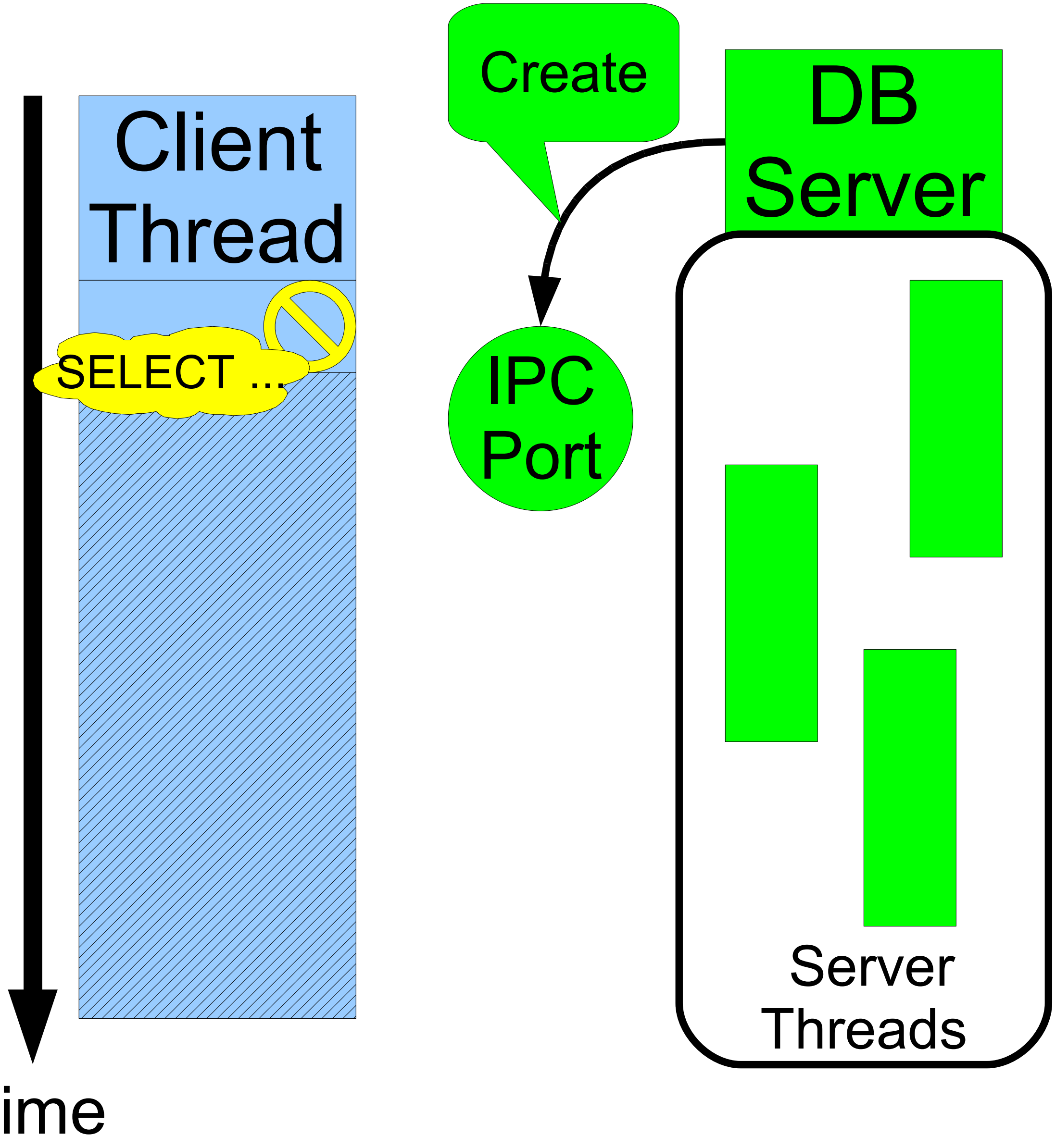


HiStar avoids file covert channels

- 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

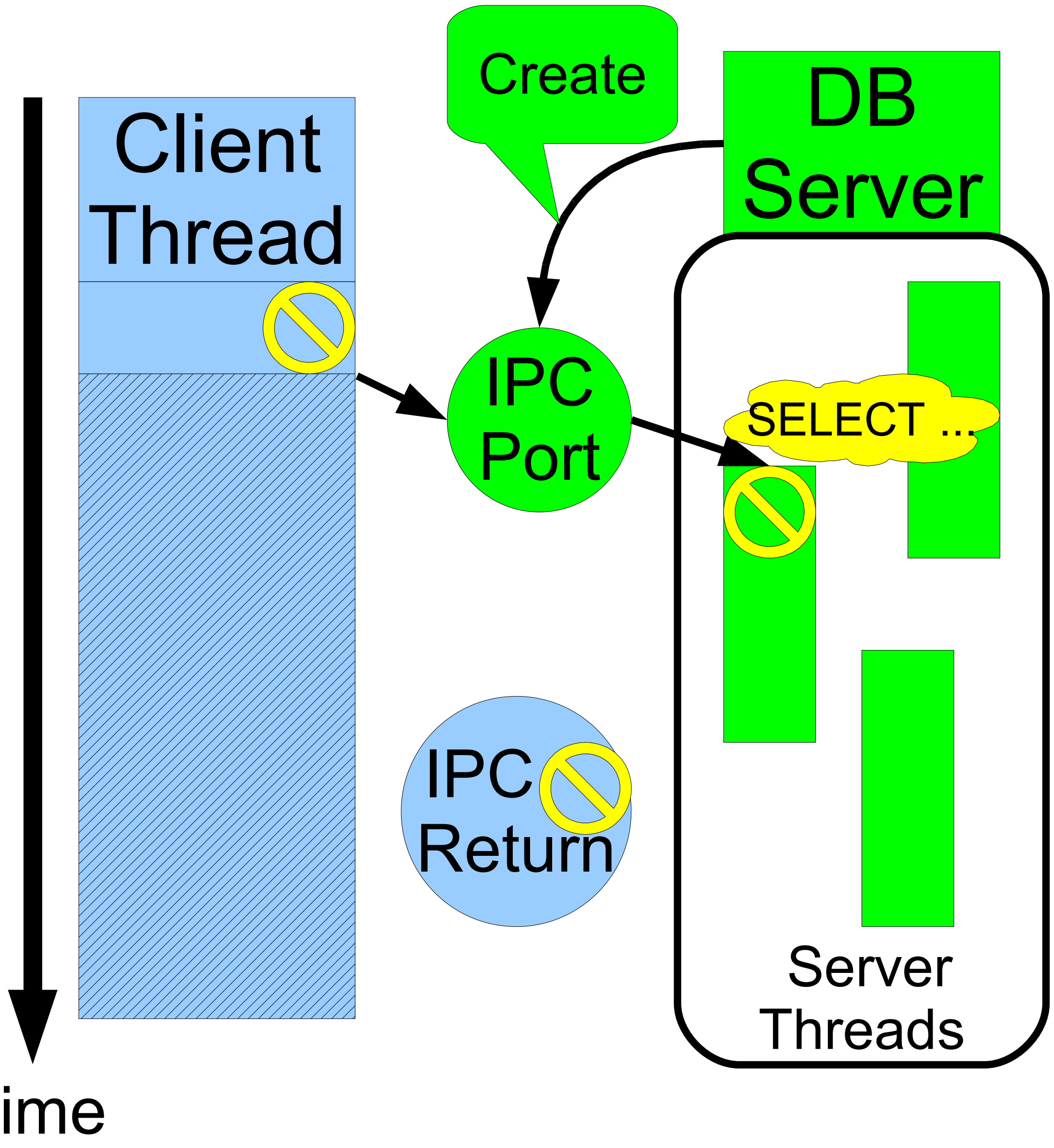
Problems with IPC

- IPC with tainted client
    - Taint server thread during request



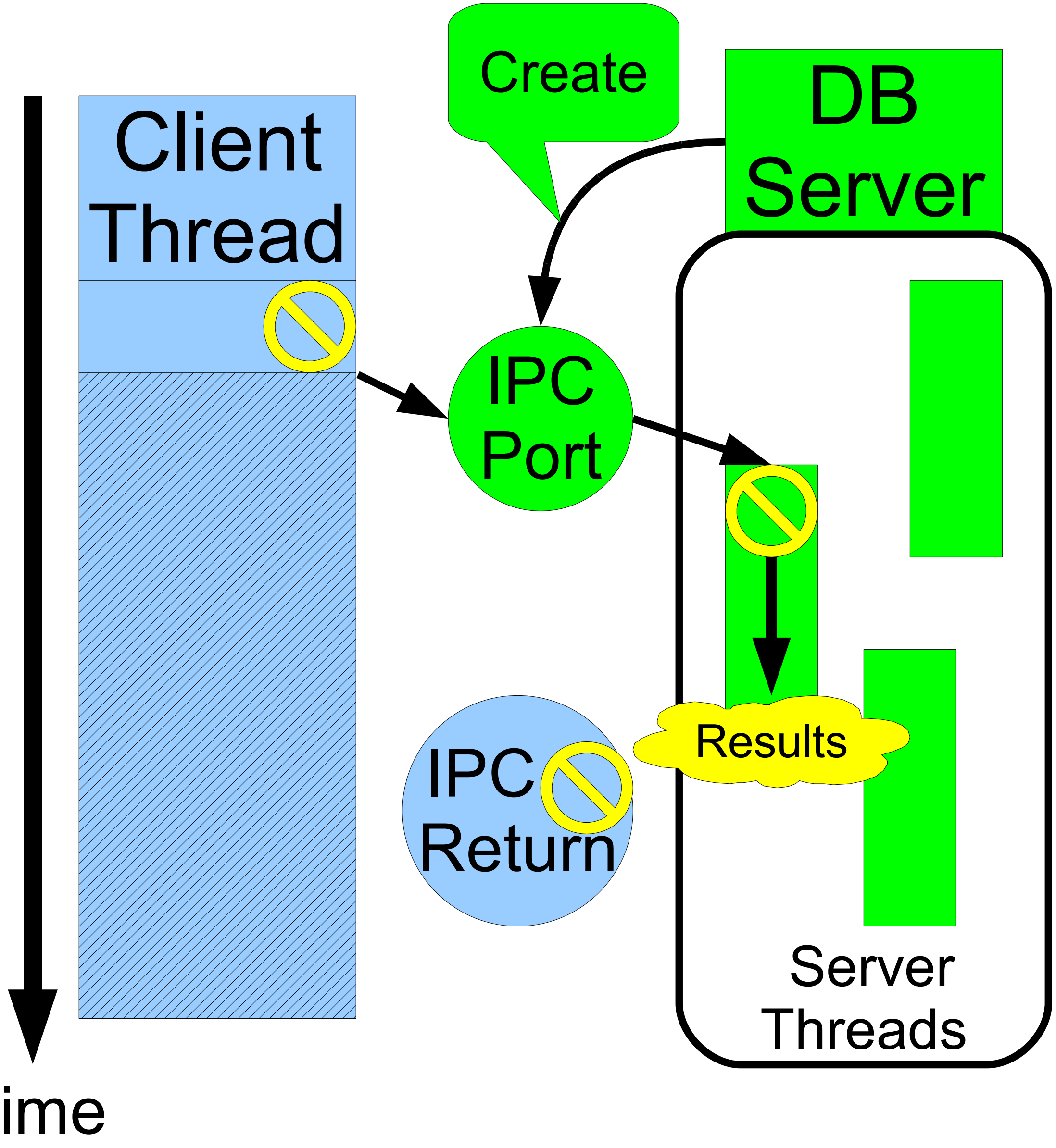
Problems with IPC

- IPC with tainted client
  - Taint server thread during request



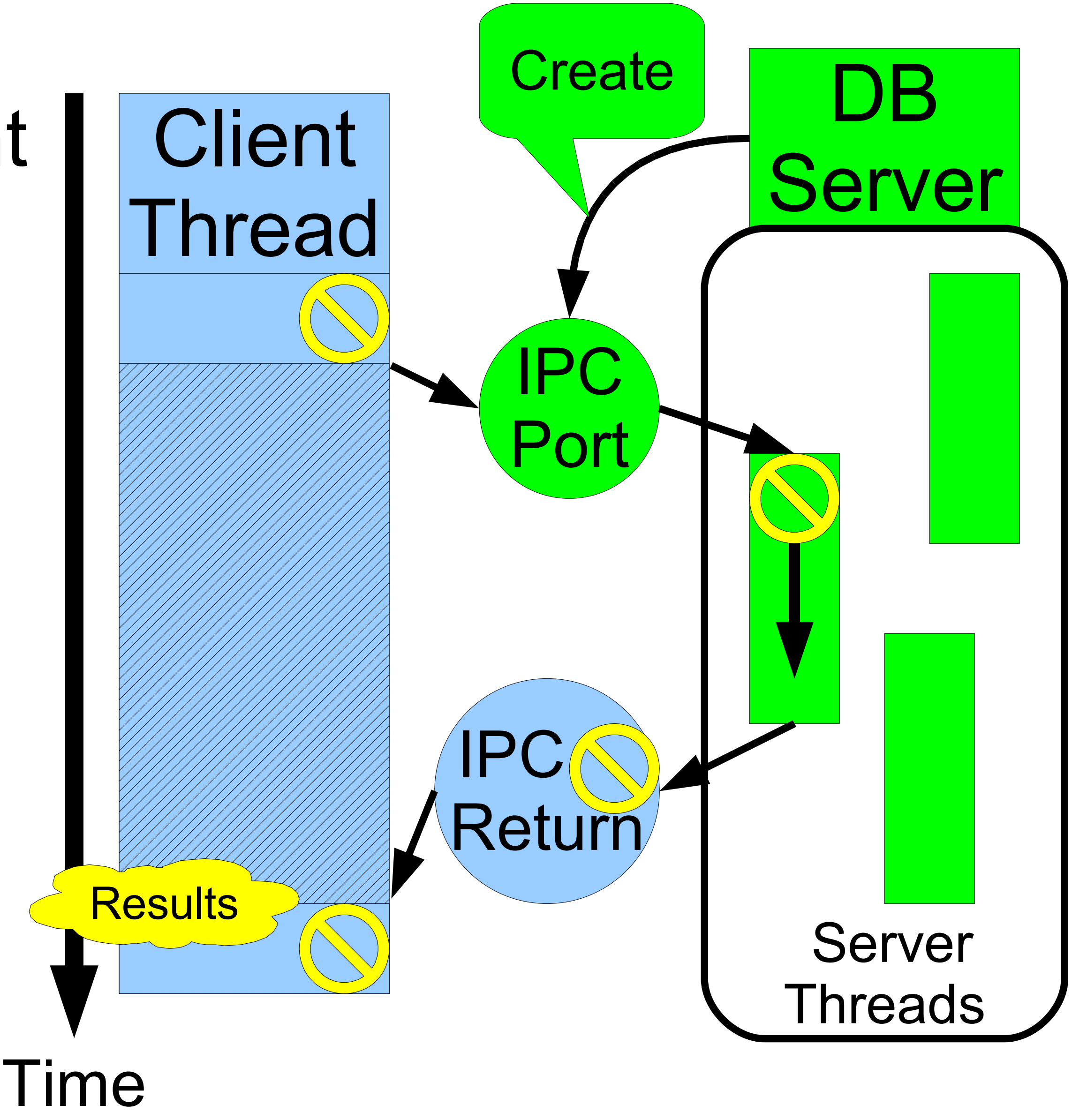
Problems with IPC

- IPC with tainted client
  - Taint server thread during request



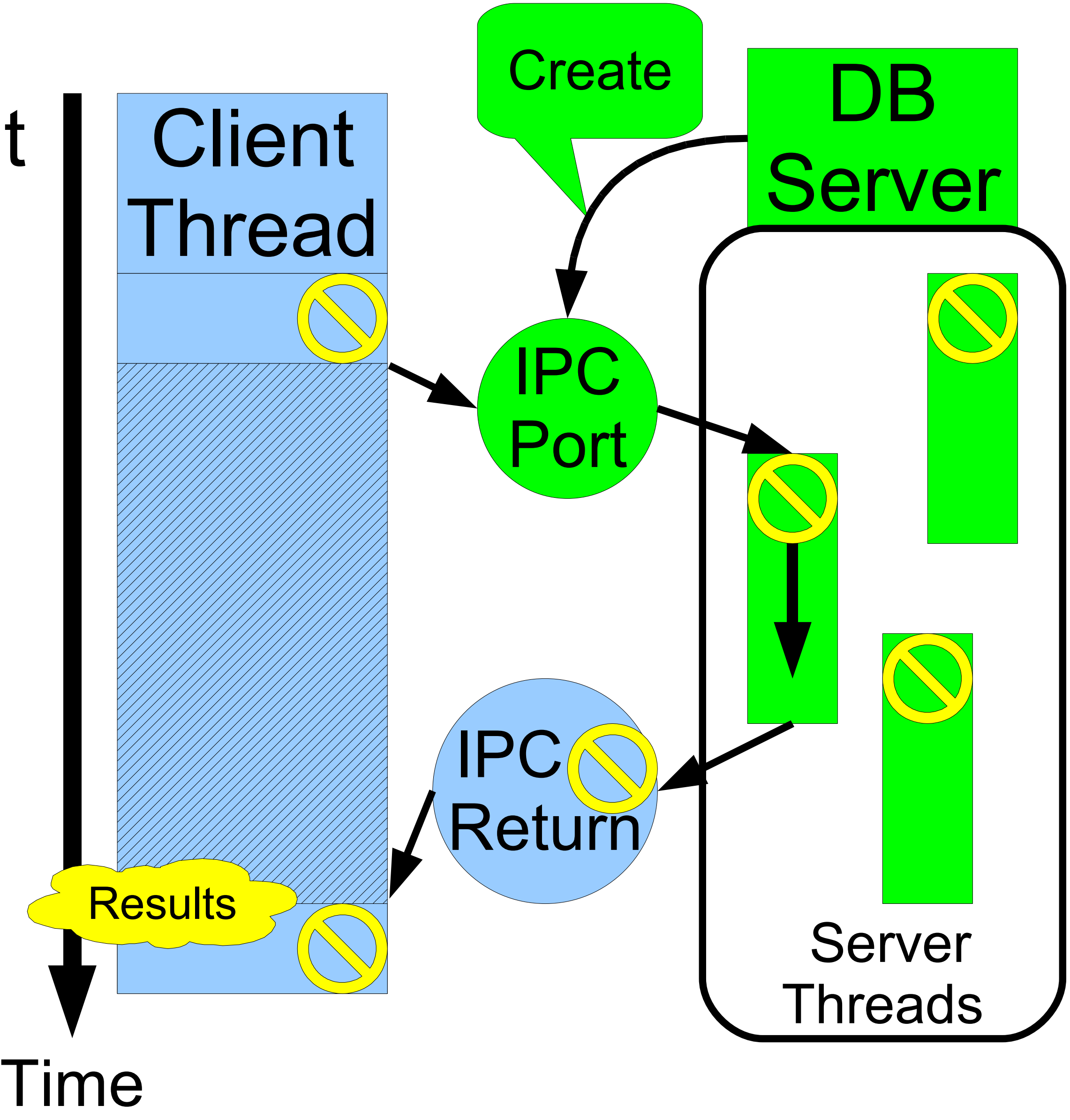
Problems with IPC

- IPC with tainted client
  - Taint server thread during request
  - Secrecy preserved?



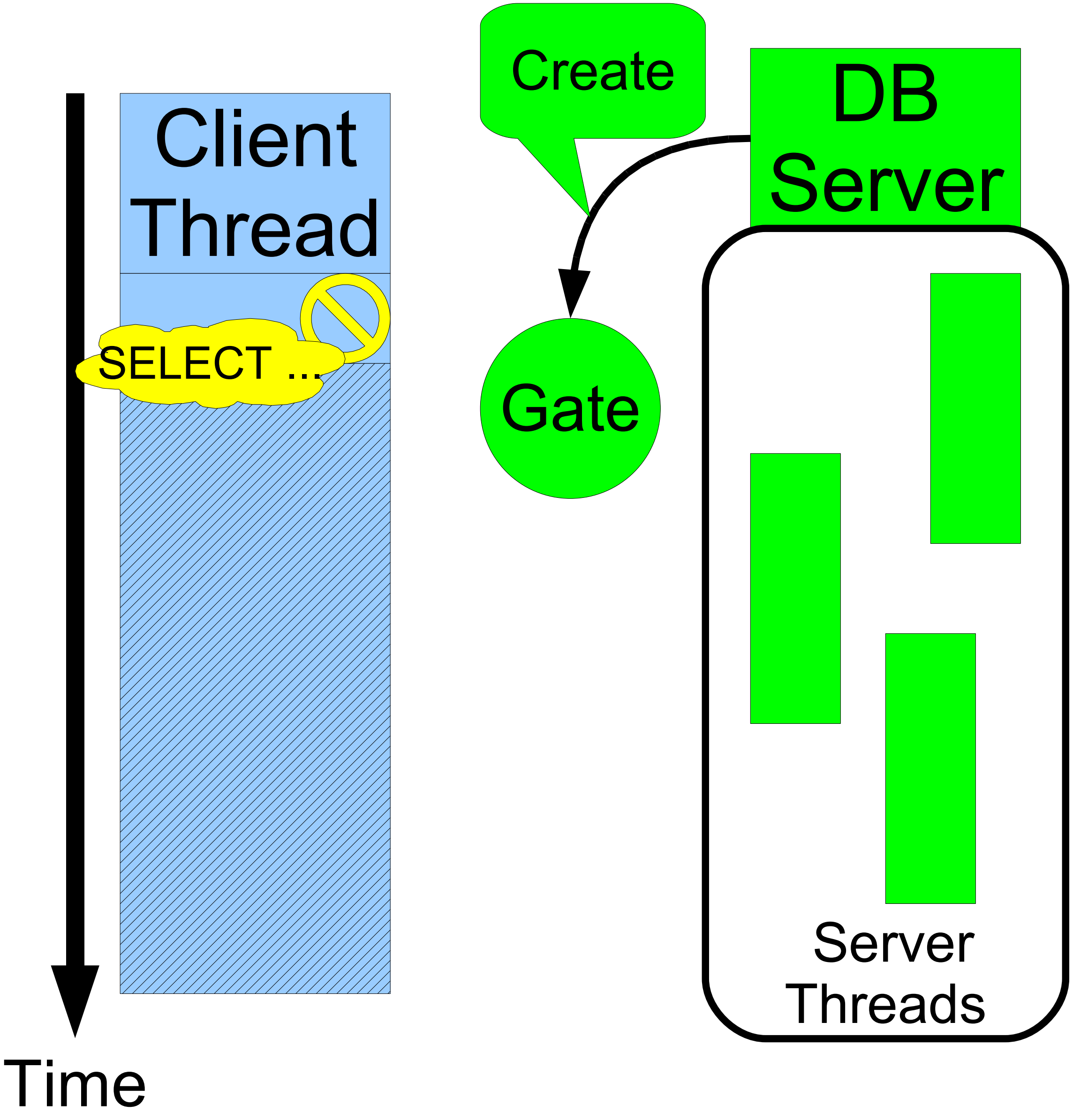
Problems with IPC

- 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!



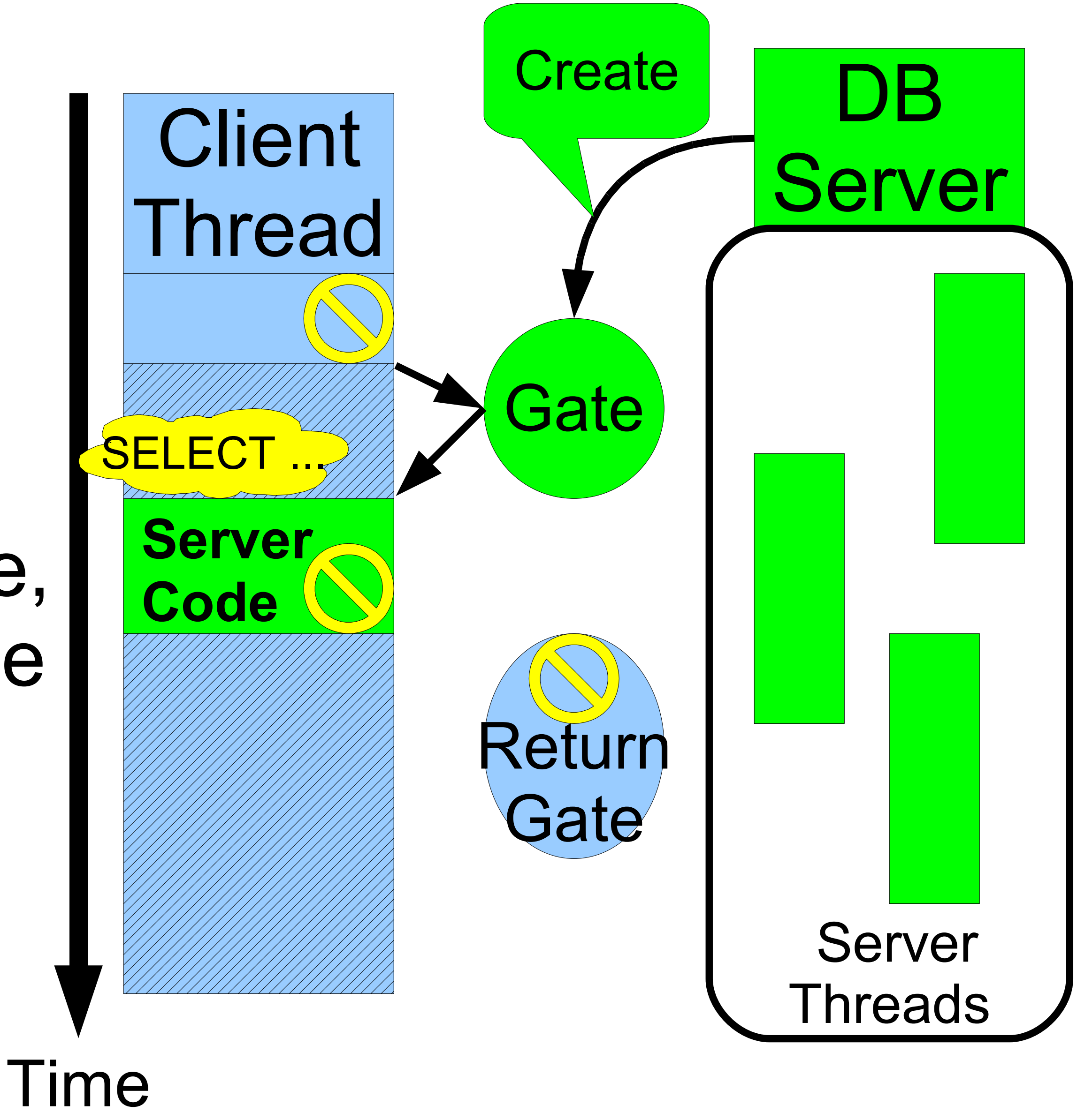
Gates make resources explicit

- Client donates initial resources (thread)



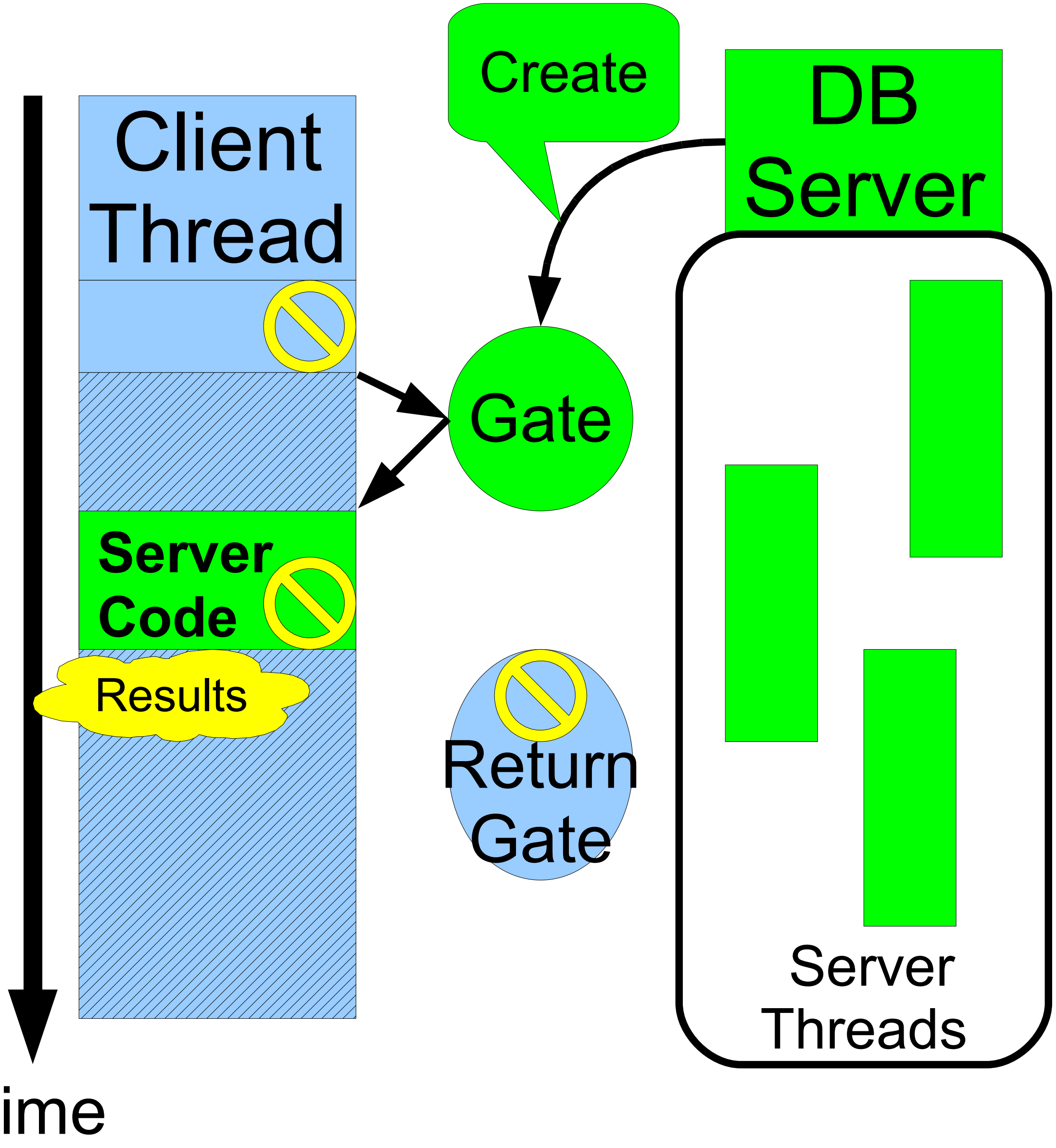
Gates make resources explicit

- Client donates initial resources (thread)
- Client thread runs in server address space, executing server code



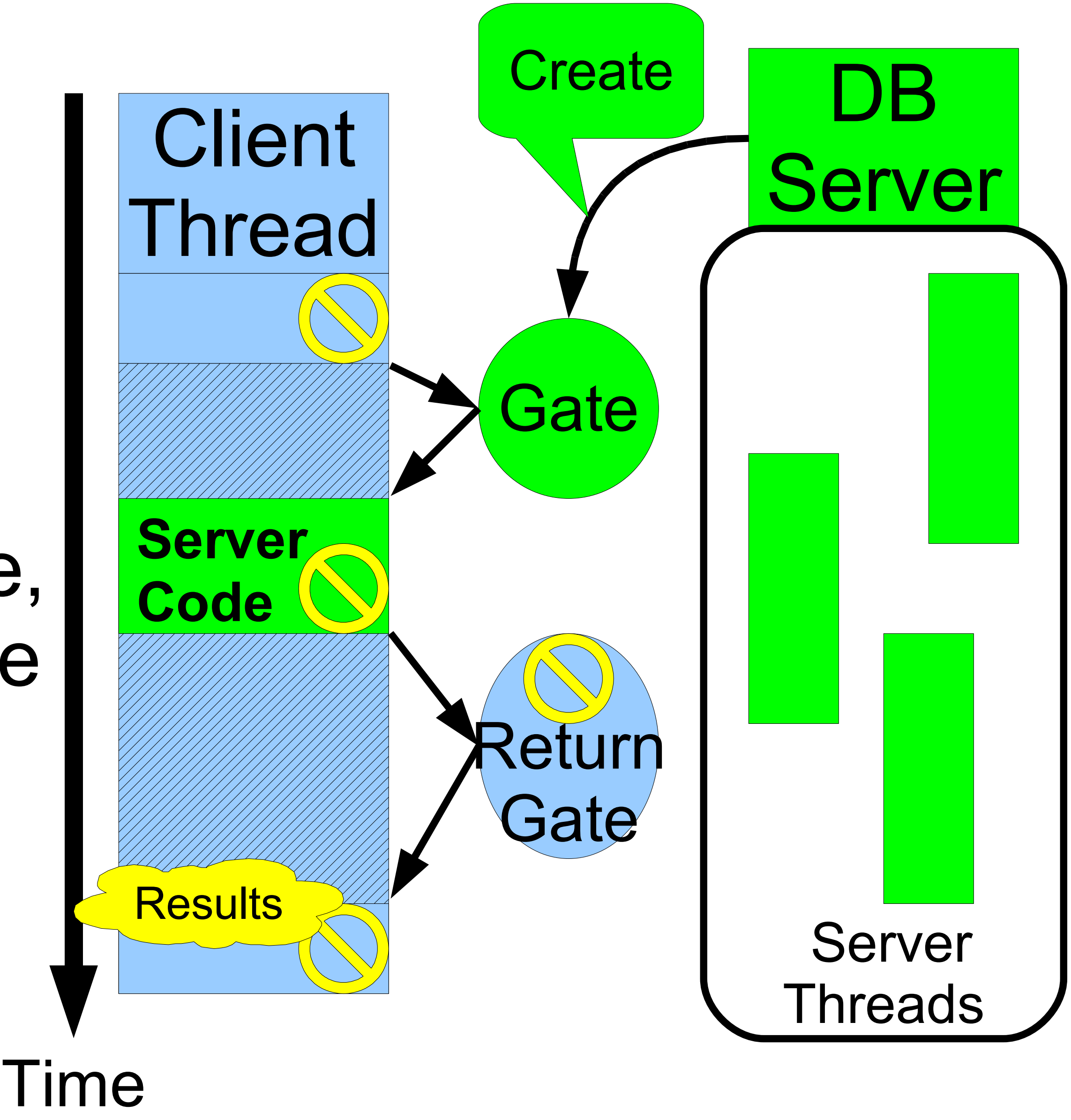
Gates make resources explicit

- Client donates initial resources (thread)
- Client thread runs in server address space, executing server code

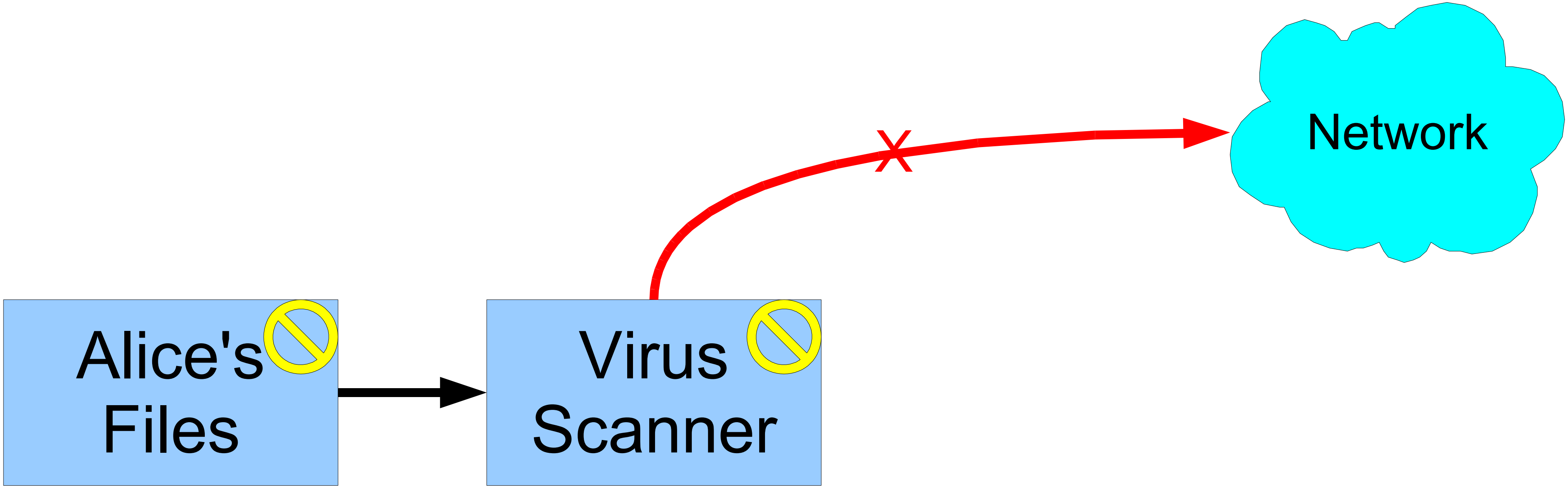


Gates make resources explicit

- Client donates initial resources (thread)
- Client thread runs in server address space, executing server code
- No implicit resource allocation – no leaks



How do we get anything out?



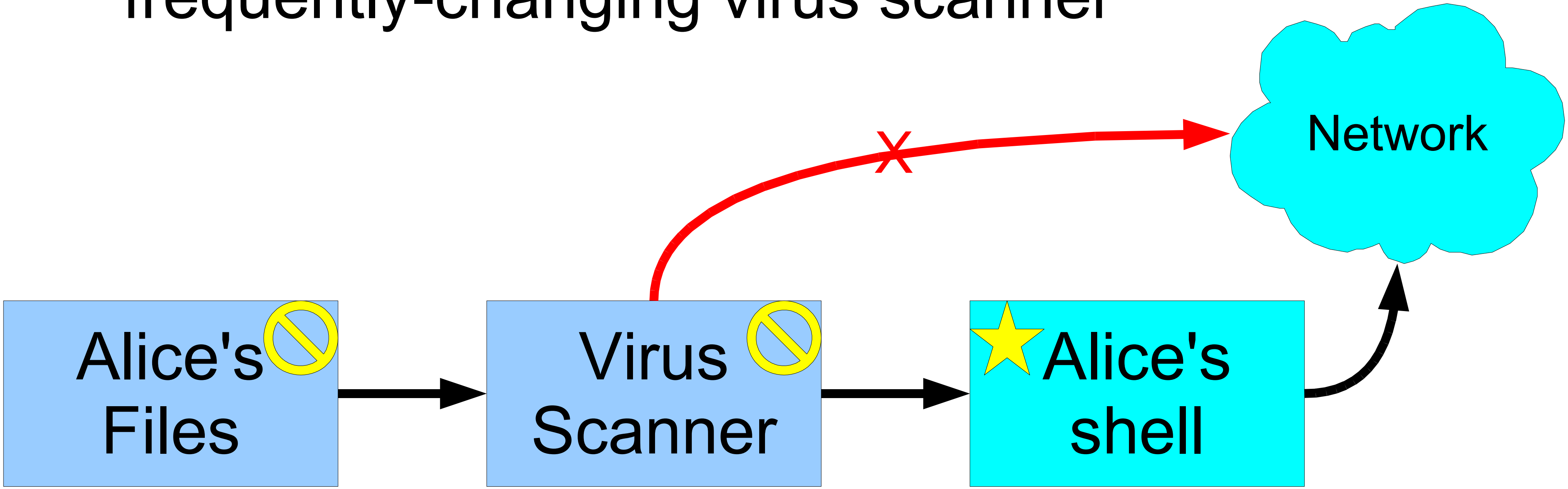
Network

Alice's Files

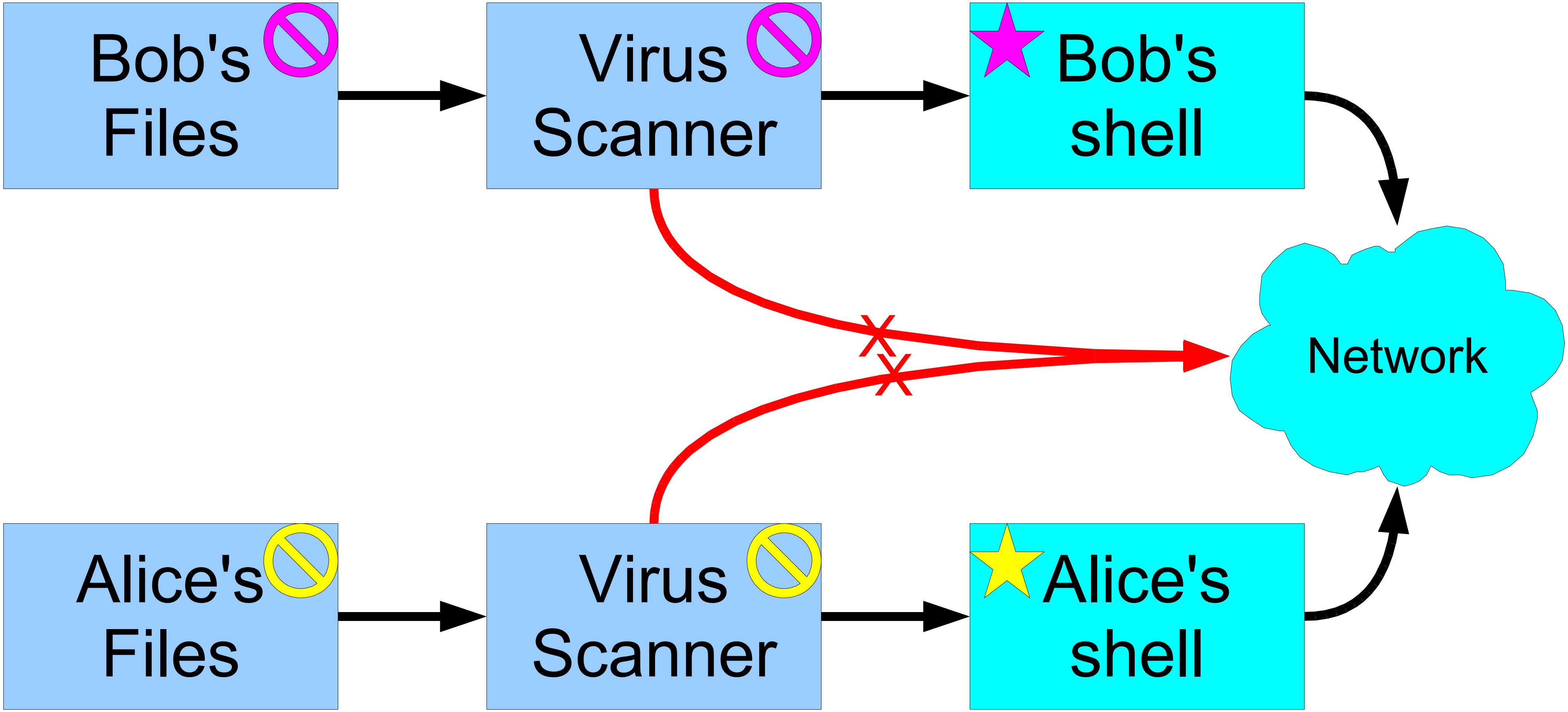
Virus Scanner

“Owner” privilege

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



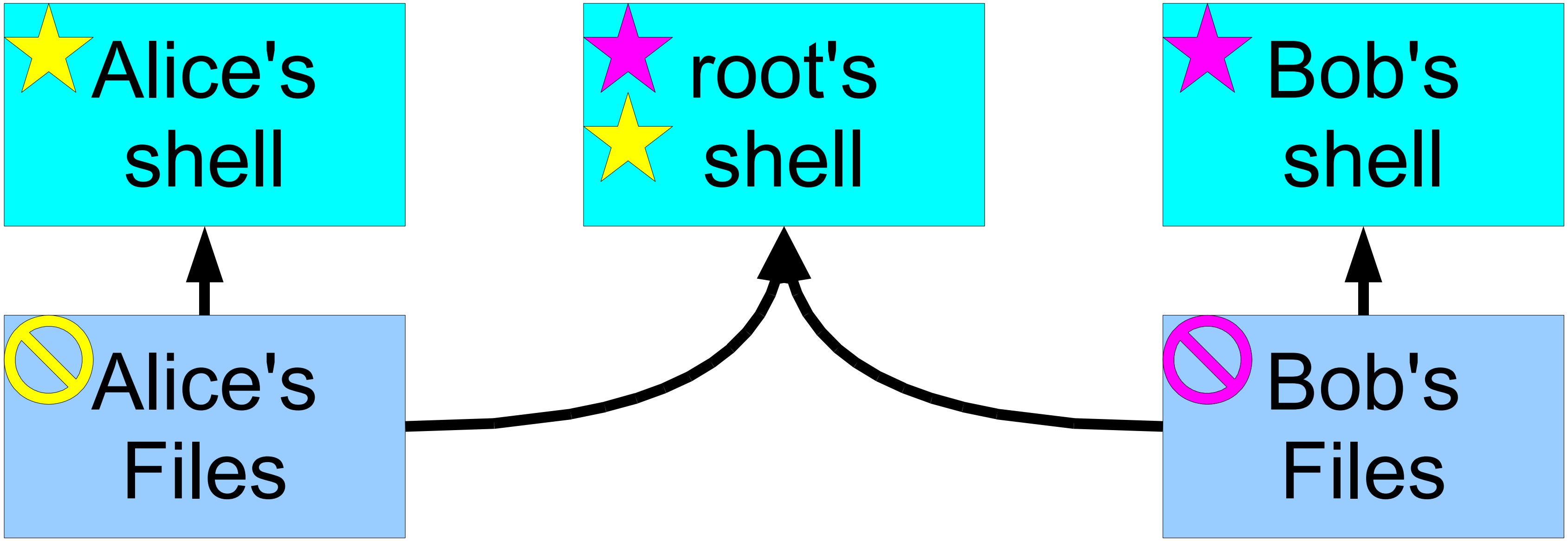
Multiple categories of taint



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

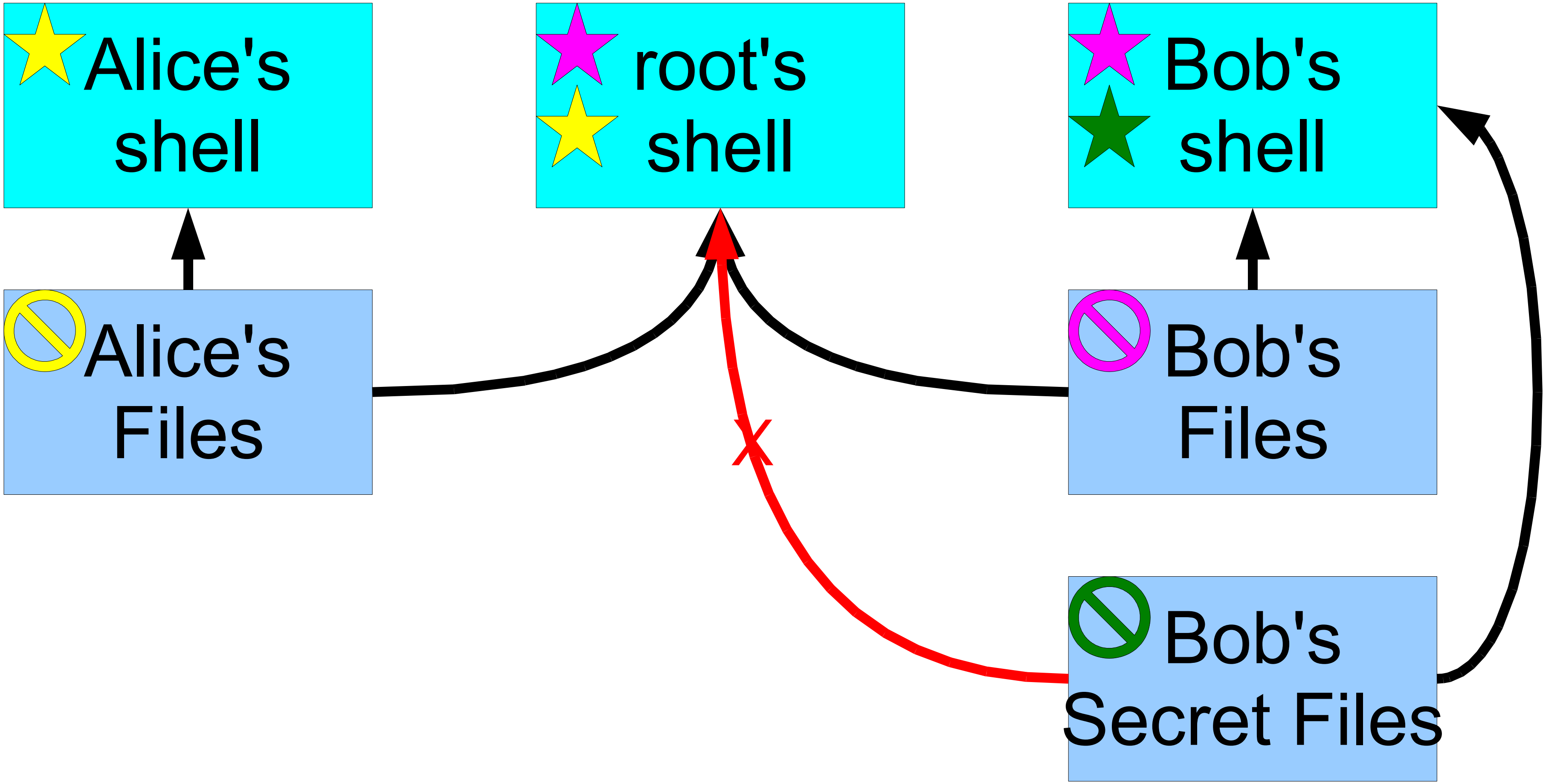
HiStar root privileges are explicit

- Kernel gives no special treatment to root



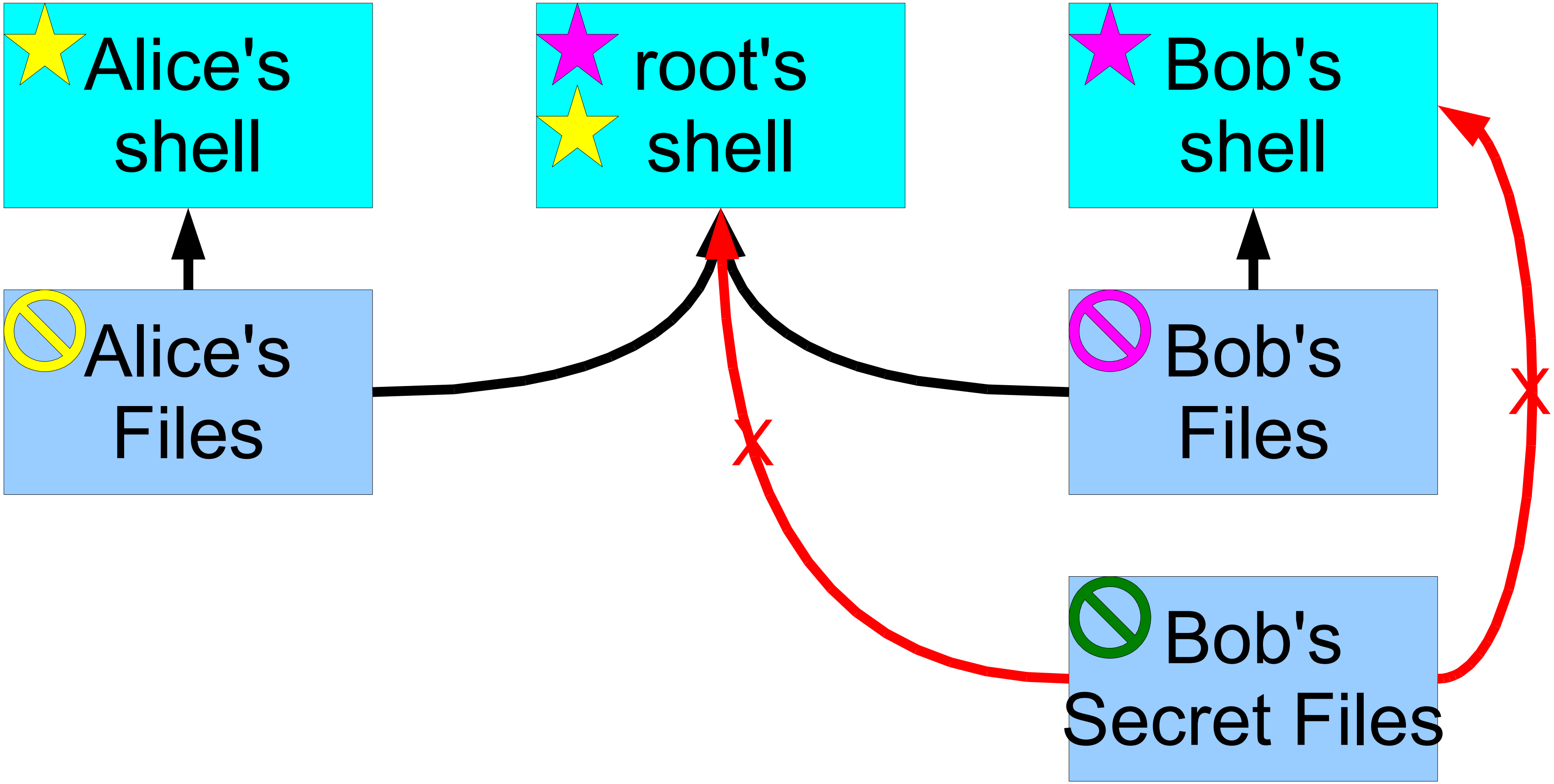
HiStar root privileges are explicit

- Users can keep secret data inaccessible to root

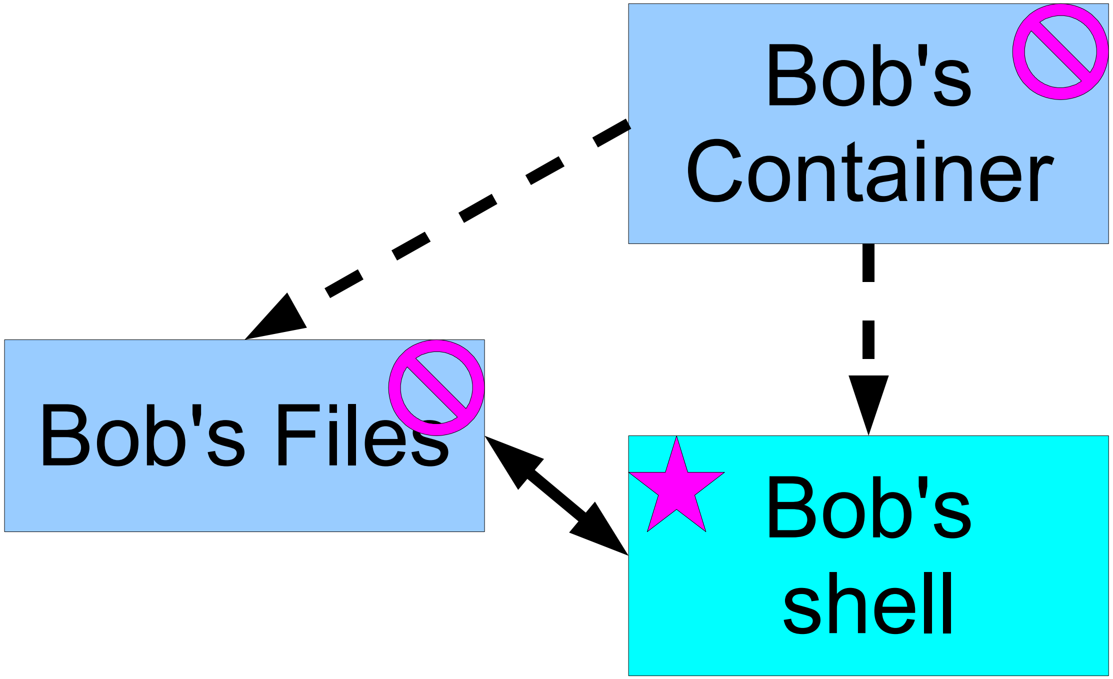


What to do with inaccessible files?

- Noone has privilege to access Bob's Secret Files



HiStar resource allocation



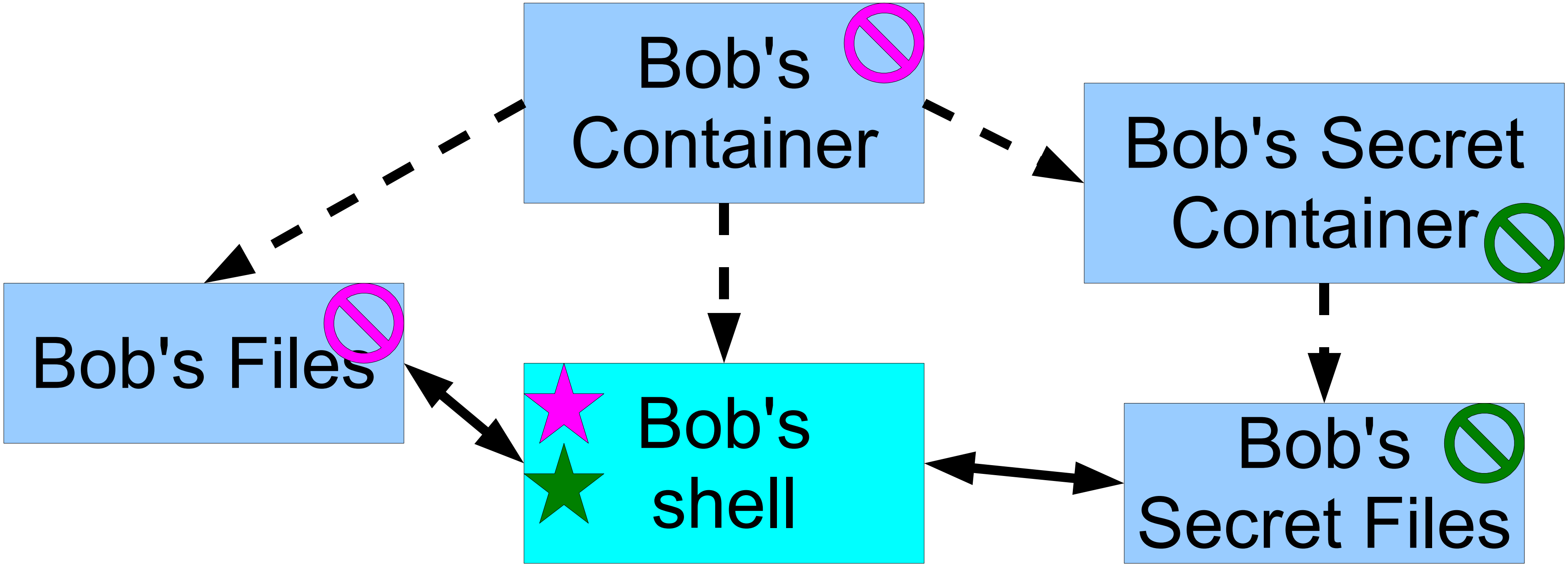
Bob's Container

Bob's Files

Bob's shell

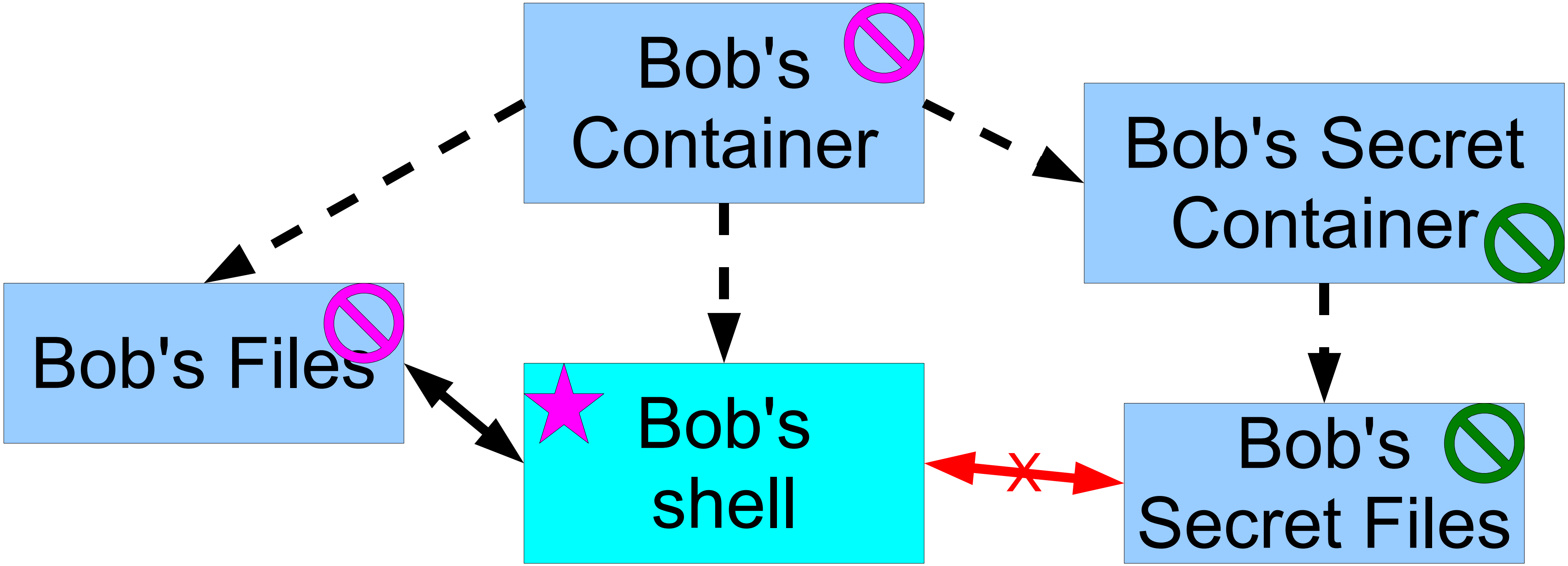
HiStar resource allocation

- Create a new sub-container for secret files



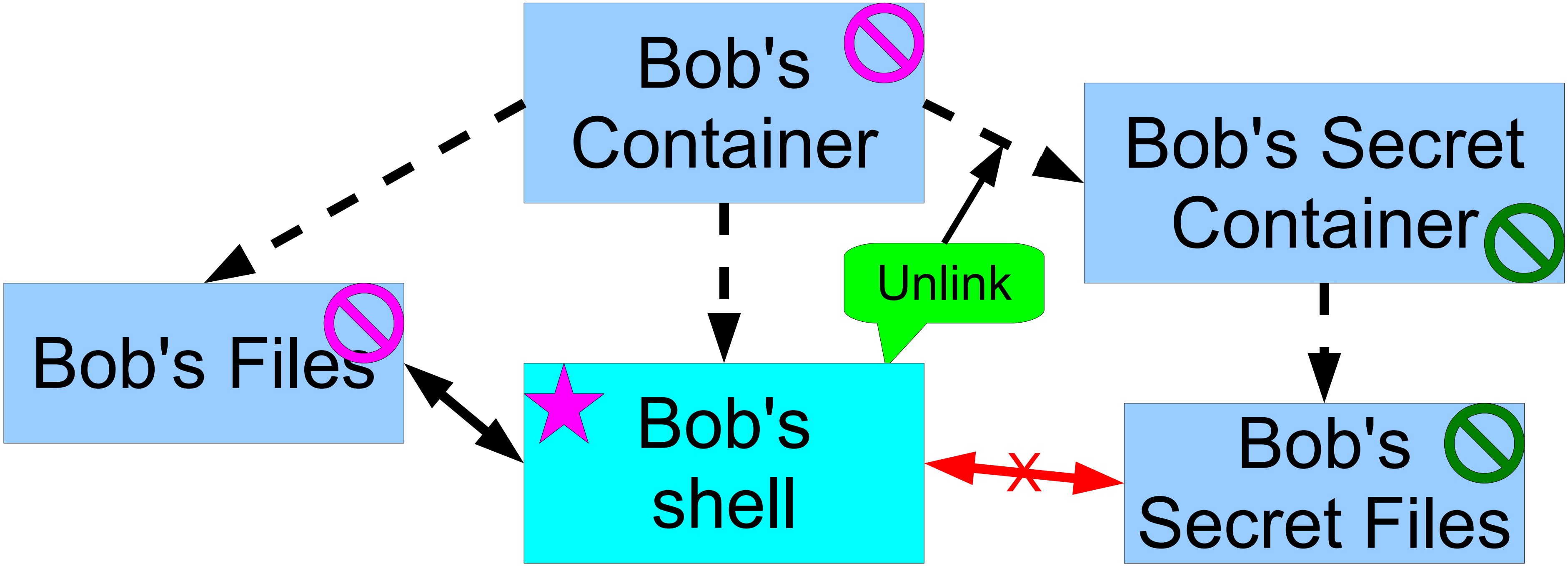
HiStar resource allocation

- Create a new sub-container for secret files



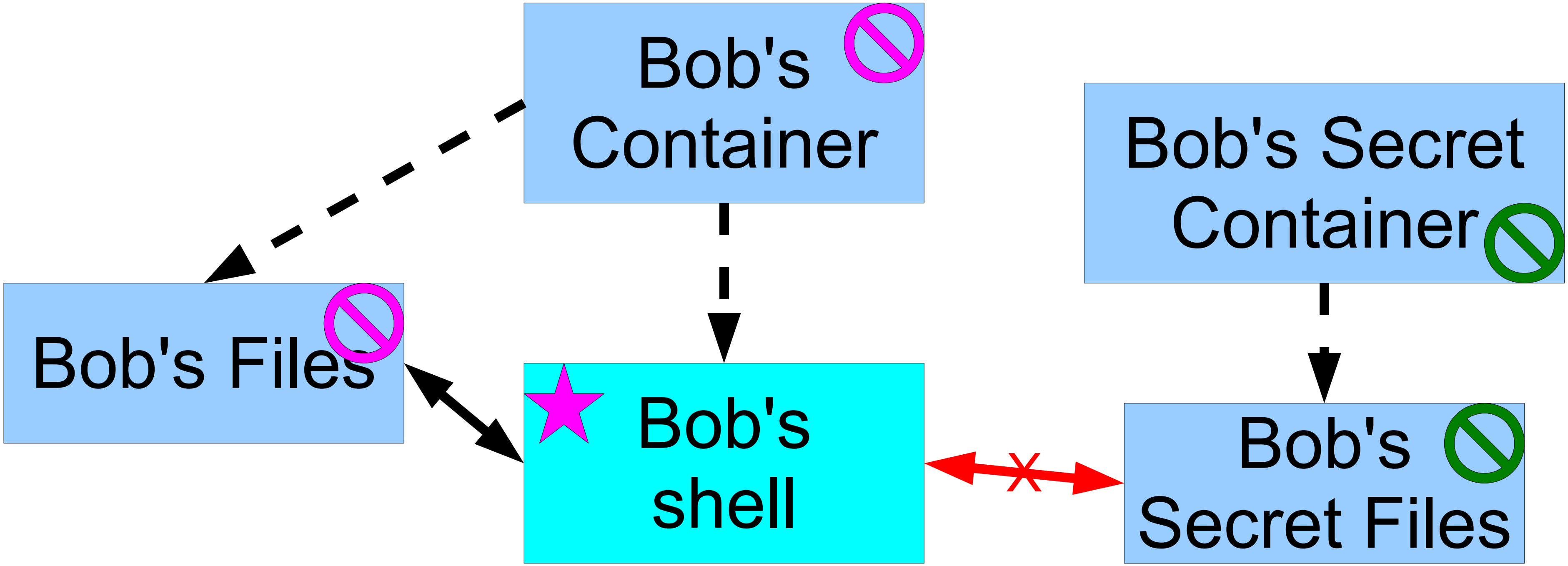
HiStar resource allocation

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



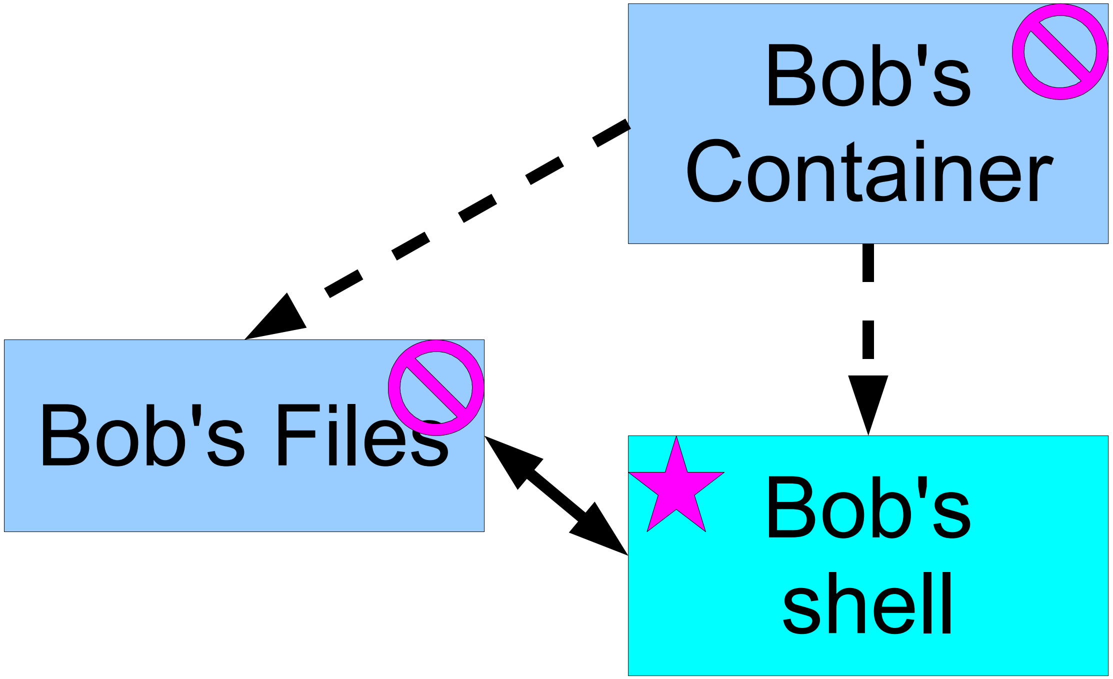
HiStar resource allocation

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



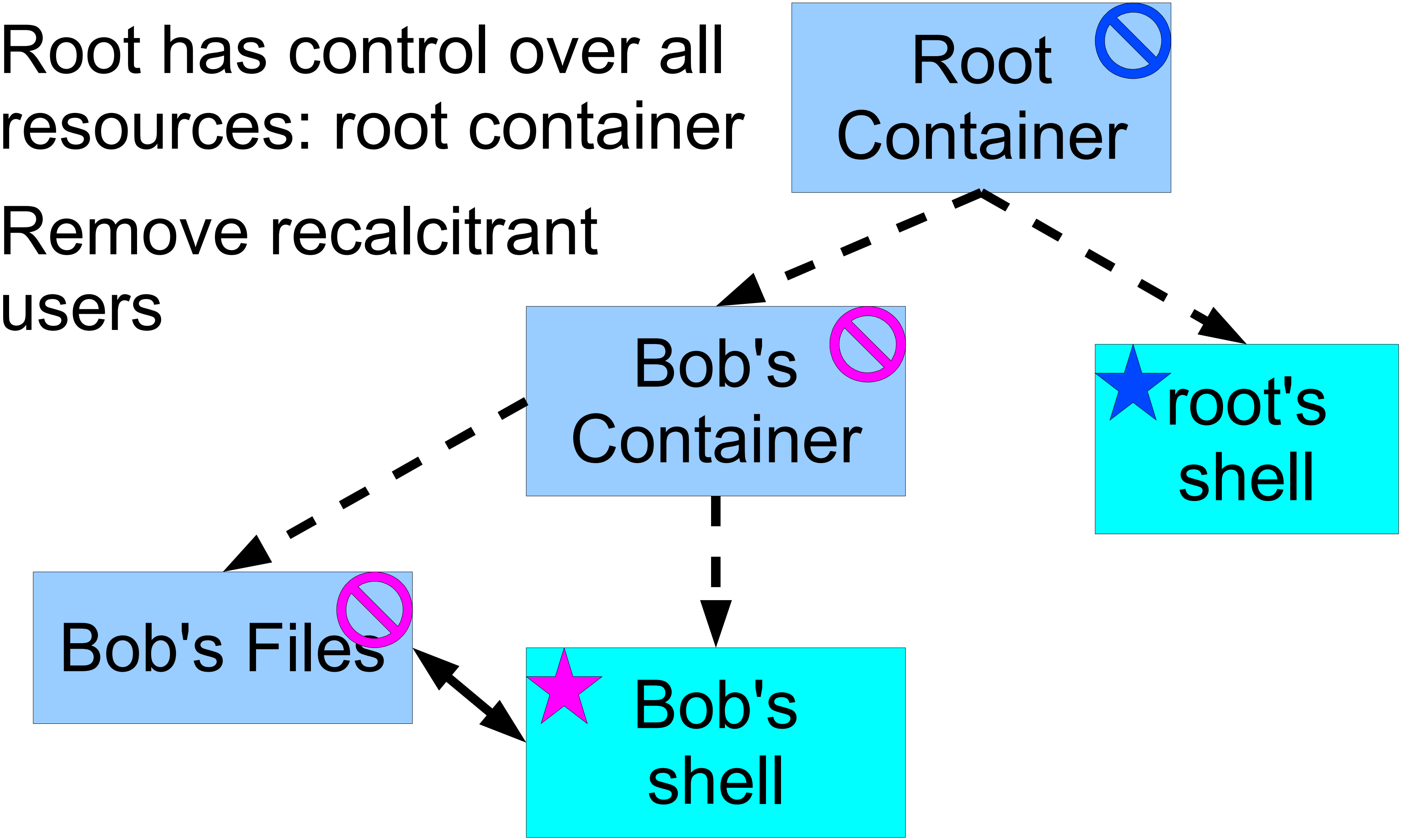
HiStar resource allocation

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



HiStar resource allocation

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



Persistent Storage

- Unix: file system implemented in the kernel
  - Potential covert channels: mtime, atime, link count, ...

- HiStar: Single-level store (like Multics / EROS)
  - All kernel objects stored on disk
  - Memory is just a cache of disk objects

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)
- ...

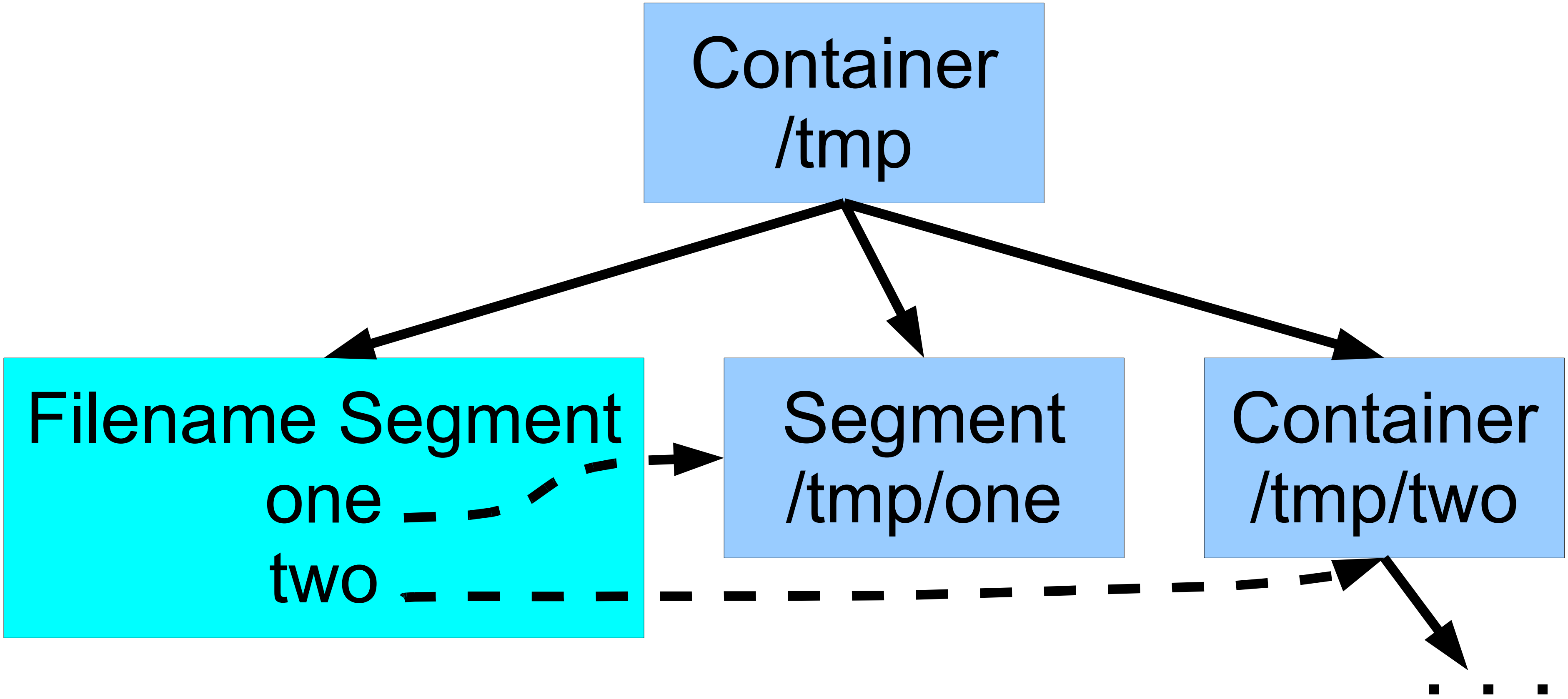
and then reboots machine

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



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

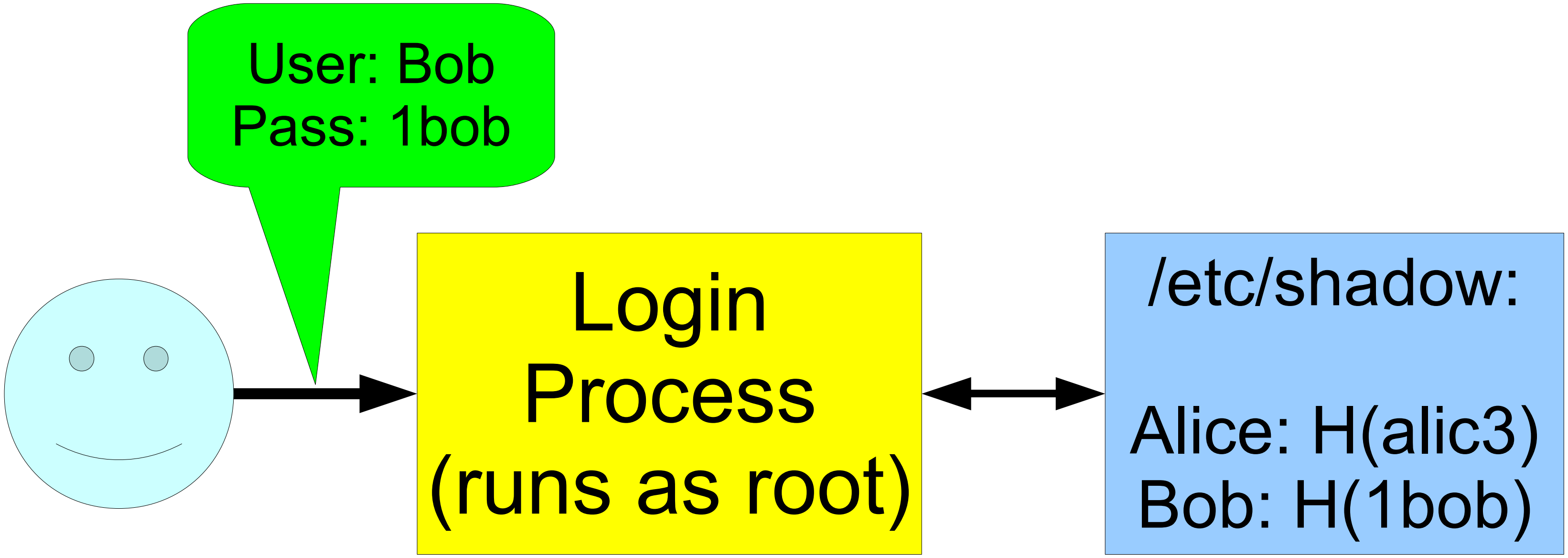
Applications

- Many Unix applications
  - gcc, gdb, openssh, ...

- High-security applications alongside with Unix
  - Untrusted virus scanners (already described)
  - VPN/Internet data separation
  - 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!



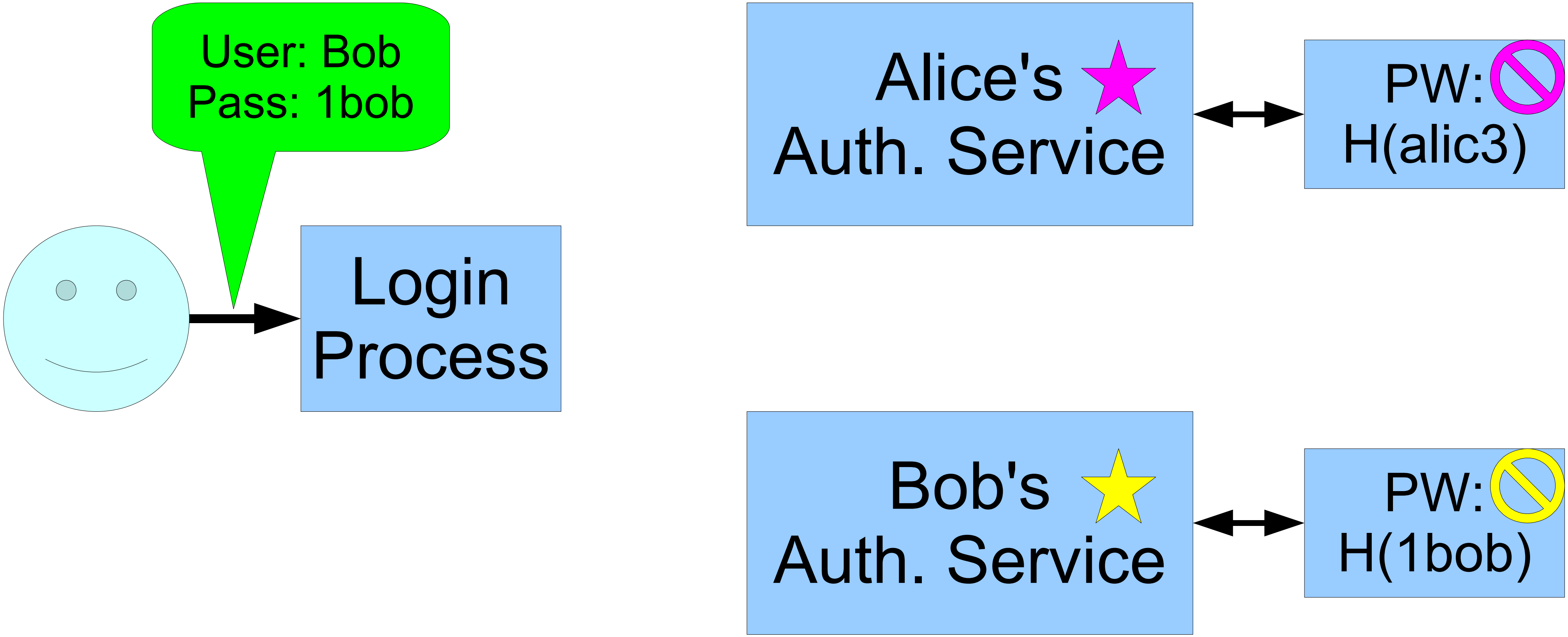
User: Bob
Pass: 1bob

Login
Process
(runs as root)

/etc/shadow:

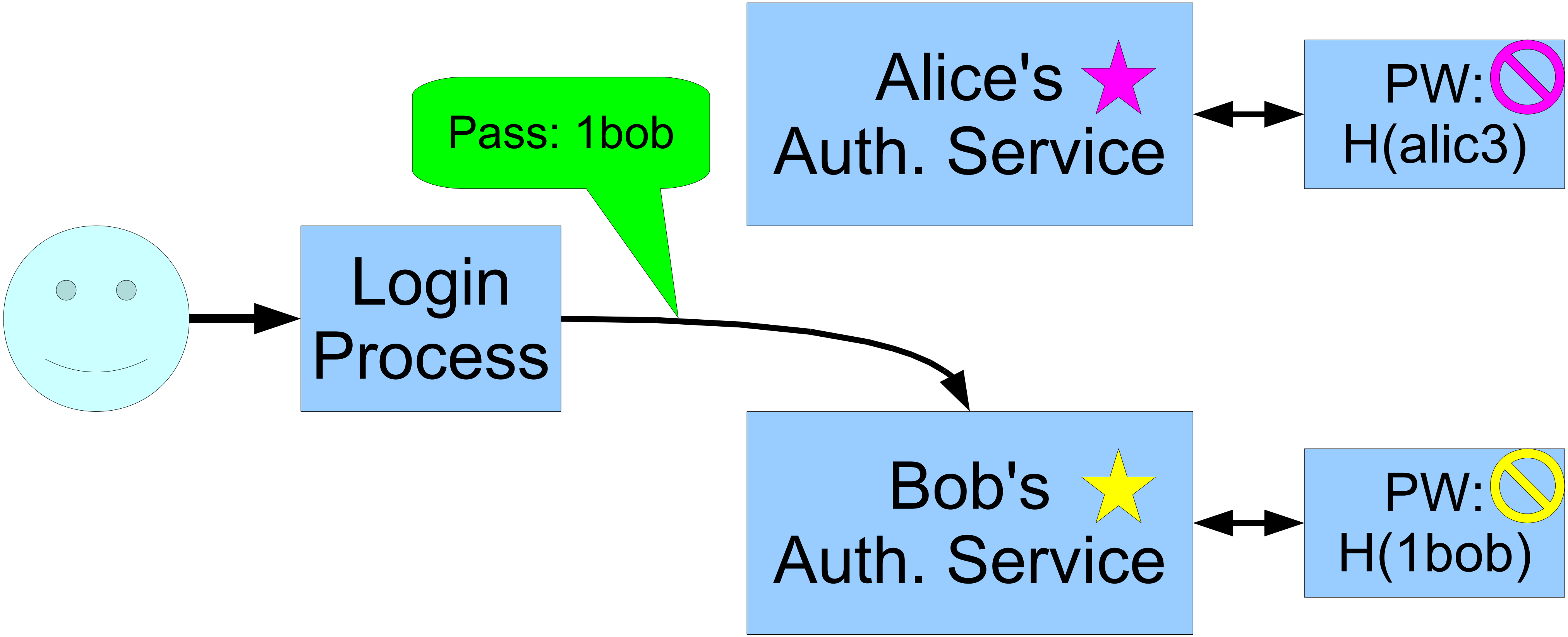
Alice: H(alic3)
Bob: H(1bob)

Login on HiStar: less trusted code



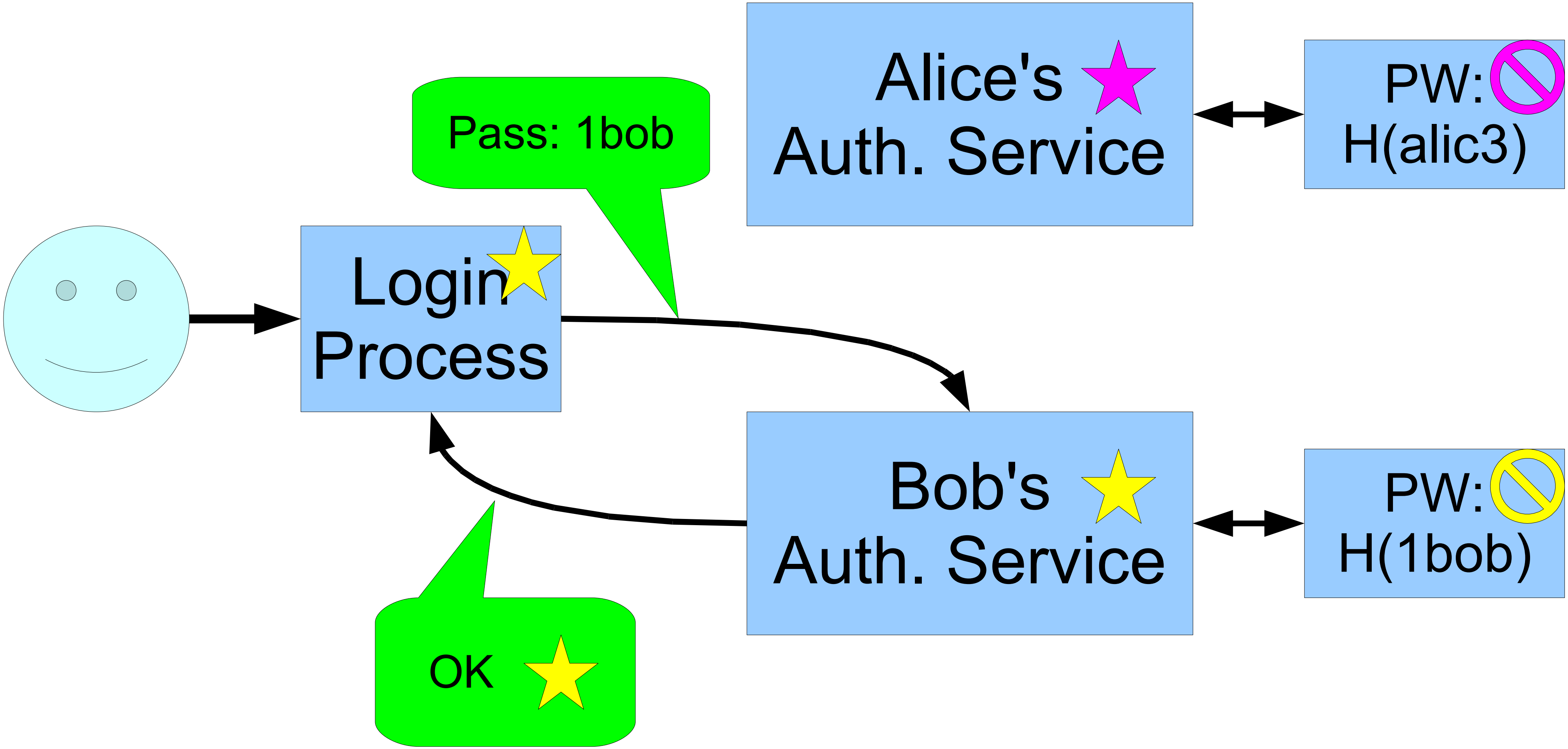
- Login process requires no privileges
- Each user can provide their own auth. service

Login on HiStar: less trusted code



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

Login on HiStar: less trusted code



Pass: 1bob

Alice's ★

Auth. Service

PW: H(alic3)

Login ★

Process

Bob's ★

Auth. Service

PW: H(1bob)

OK ★

Login on HiStar: less trusted code

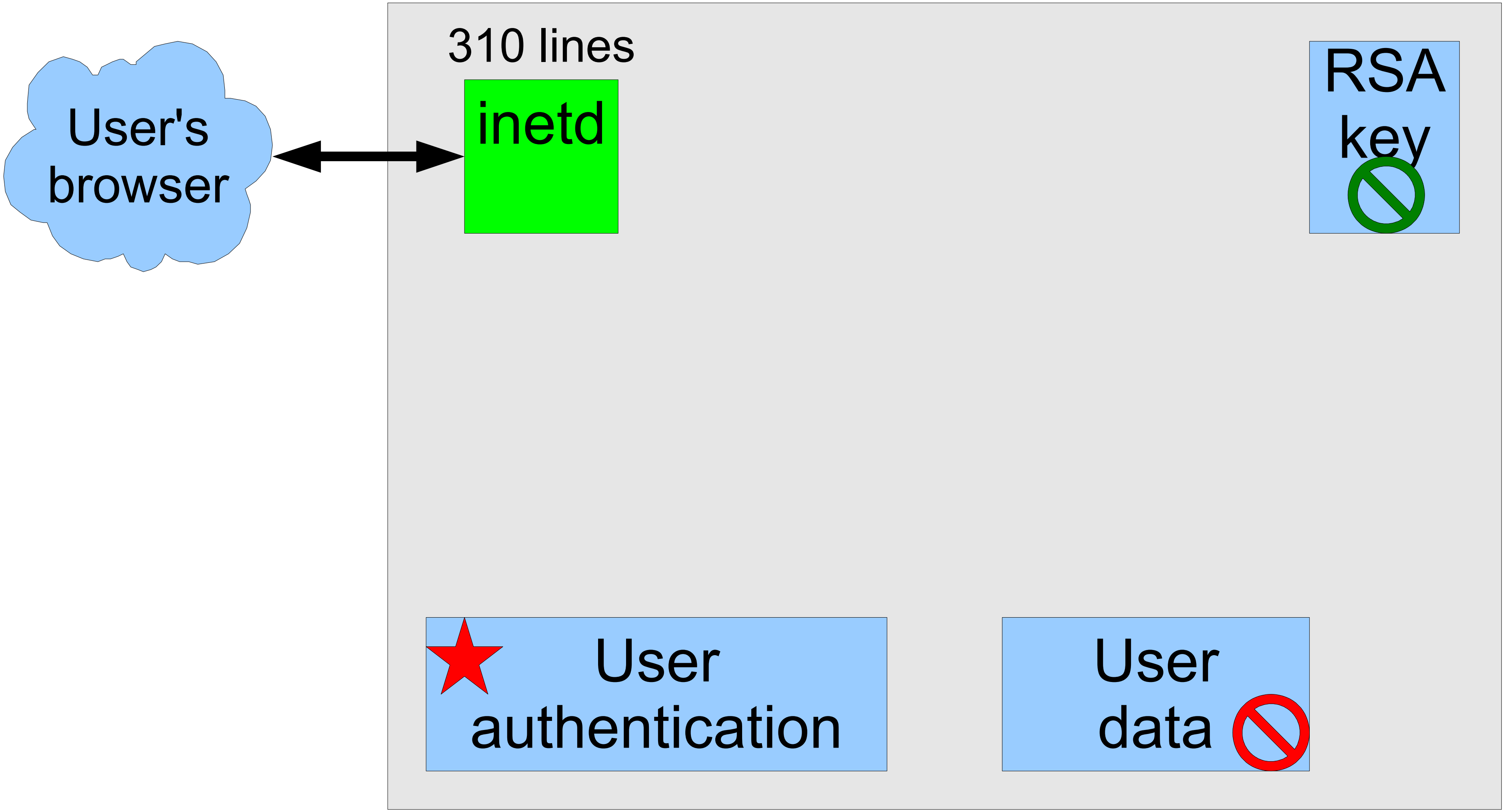
- No code runs with every user's privilege

- Users supply their own authentication code
  - Password checker, one-time passwords, ...

- OS ensures password is not disclosed
  - Even if user mistypes username, gives password to attacker's authentication code (not described)

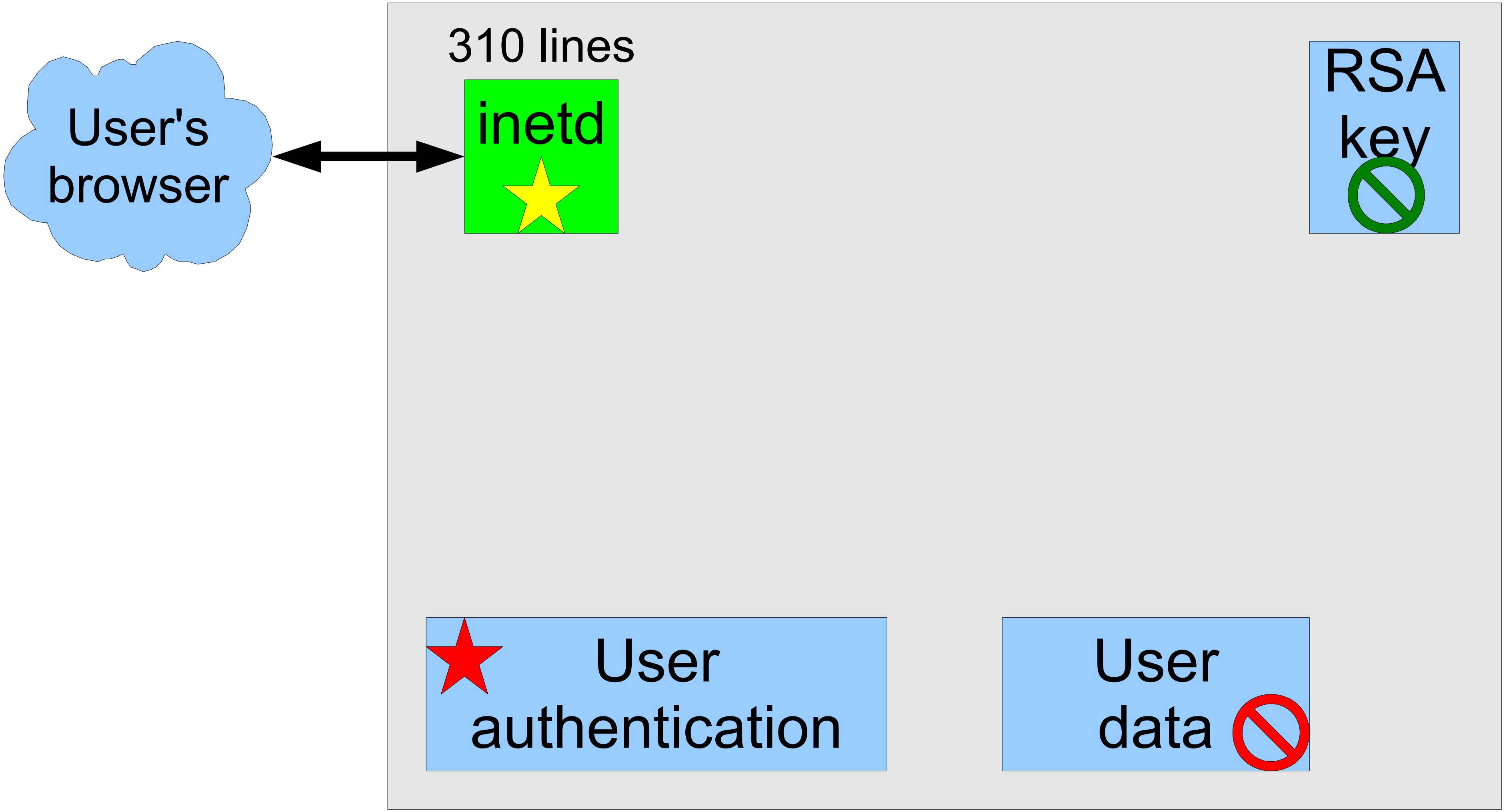
HiStar SSL Web Server

- Only small fraction of code (green) is trusted



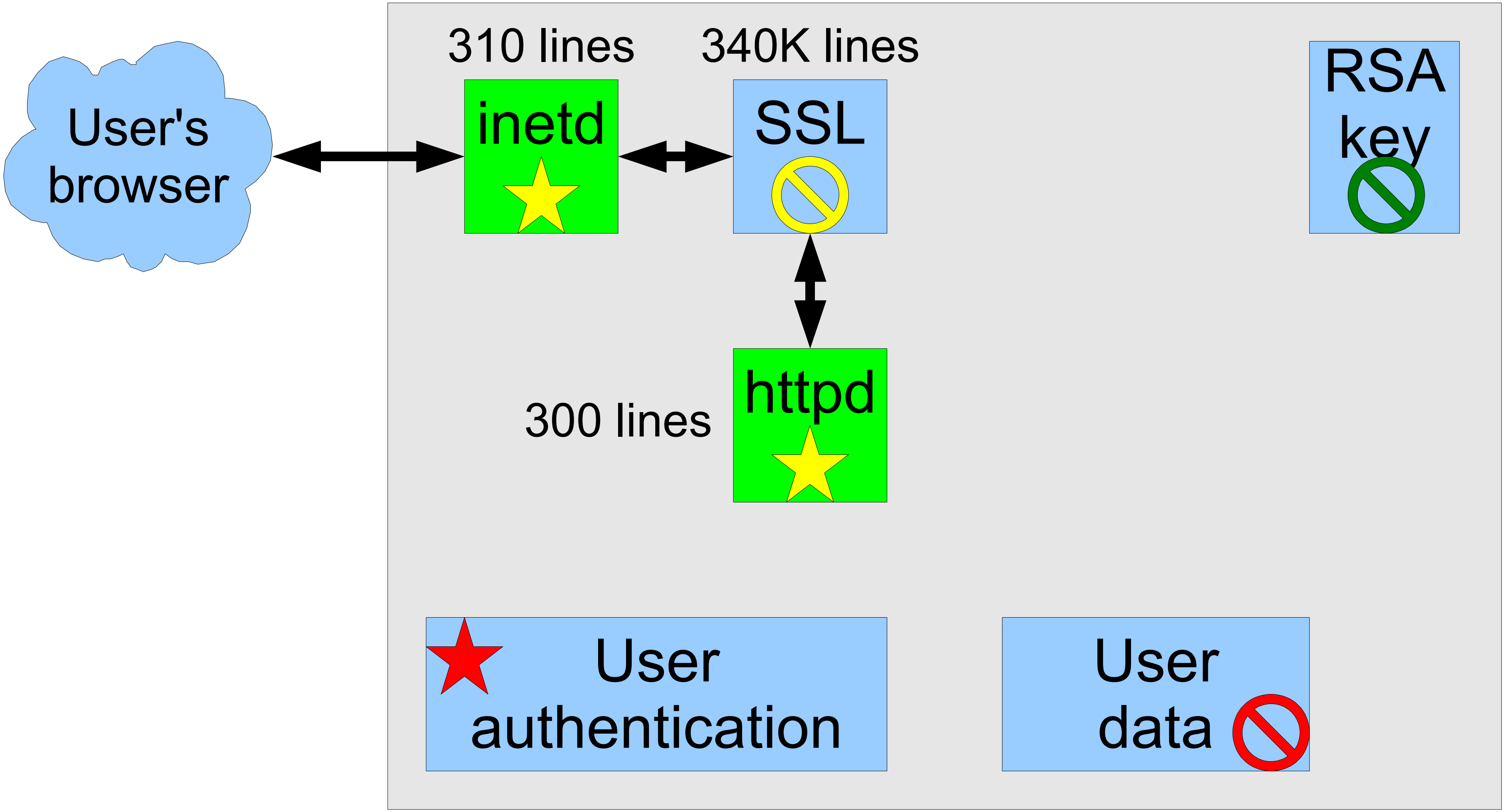
HiStar SSL Web Server

- Only small fraction of code (green) is trusted



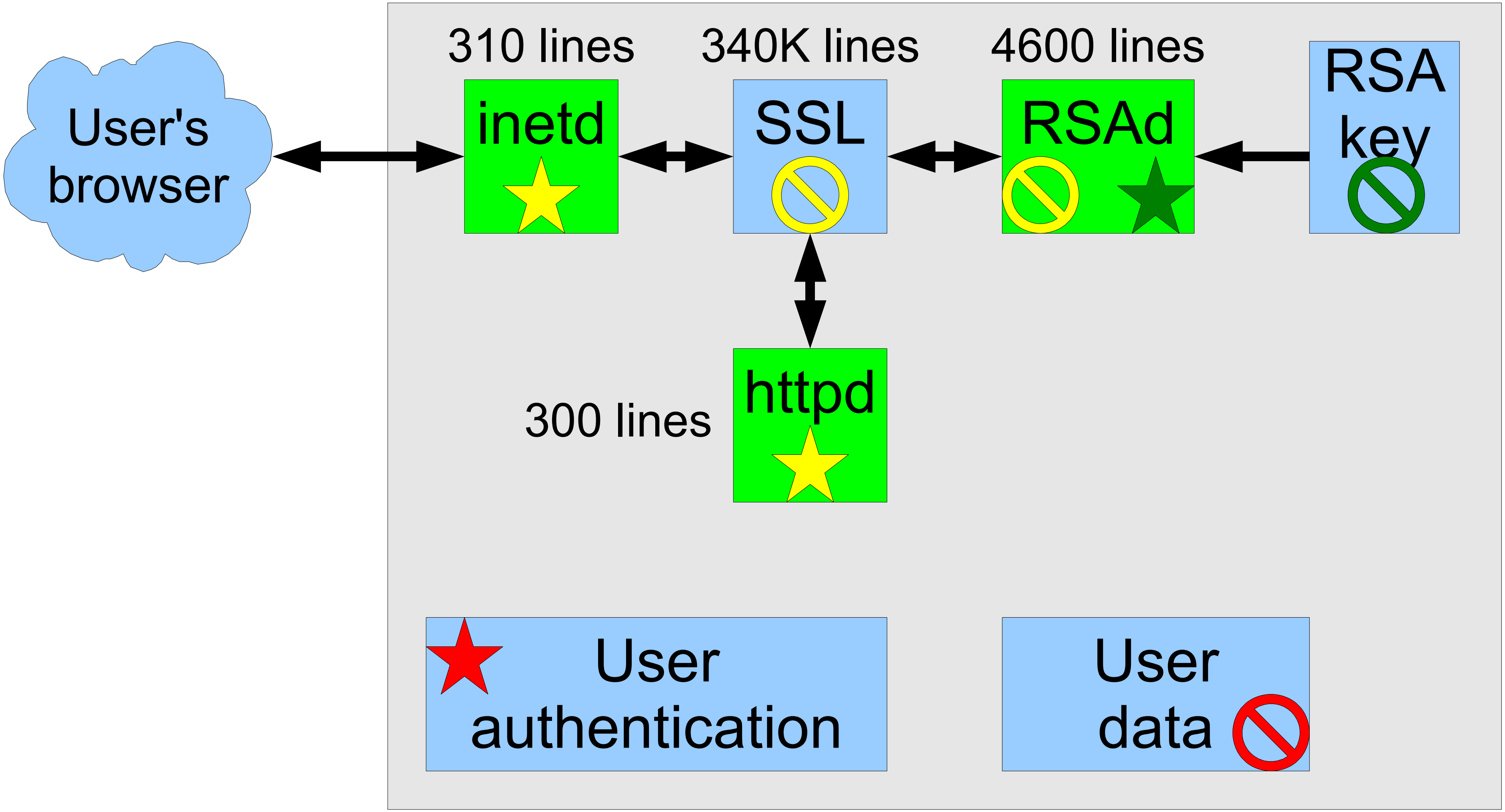
HiStar SSL Web Server

- OpenSSL only trusted to encrypt/decrypt



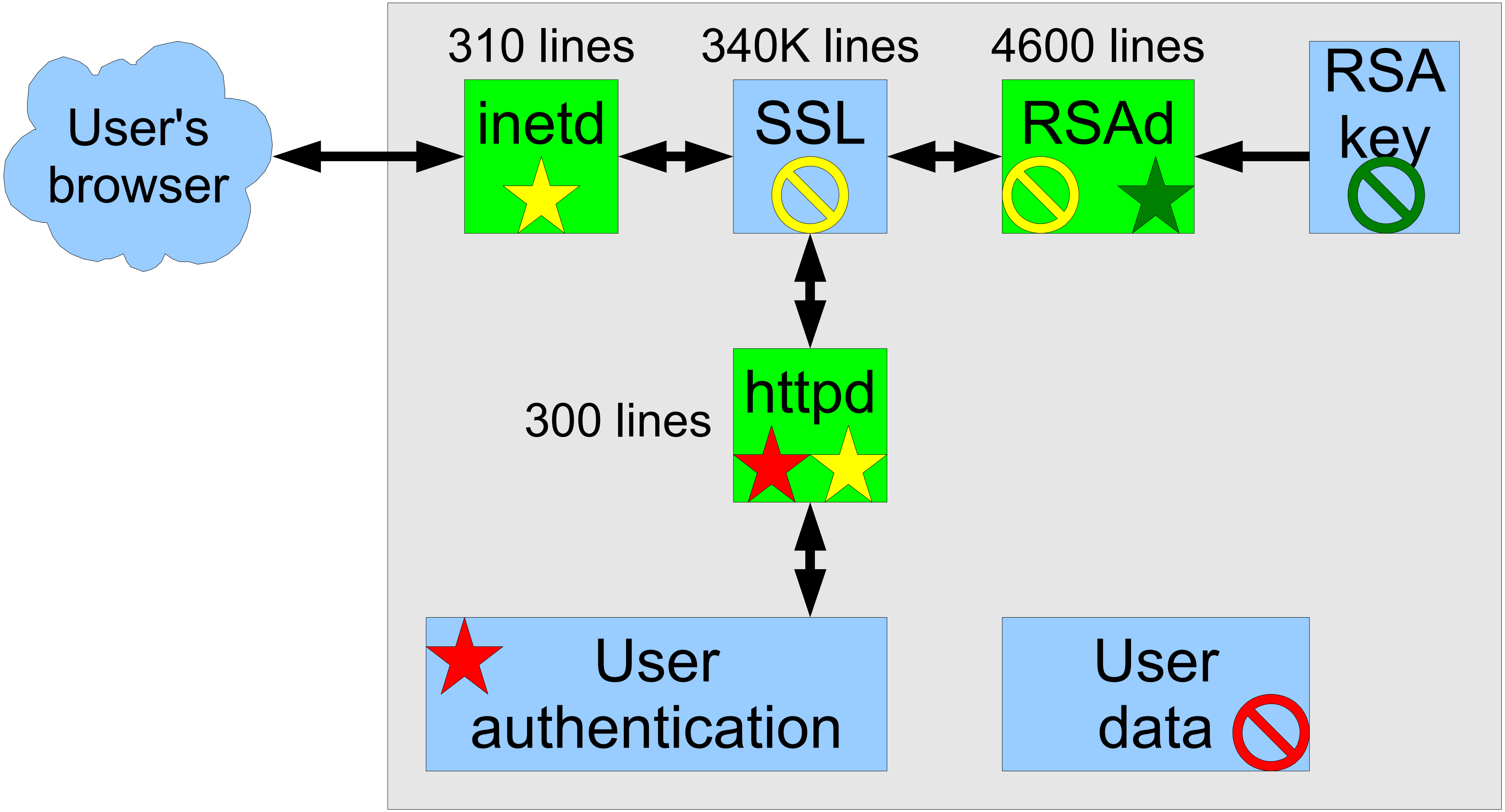
HiStar SSL Web Server

- OpenSSL cannot disclose certificate private key



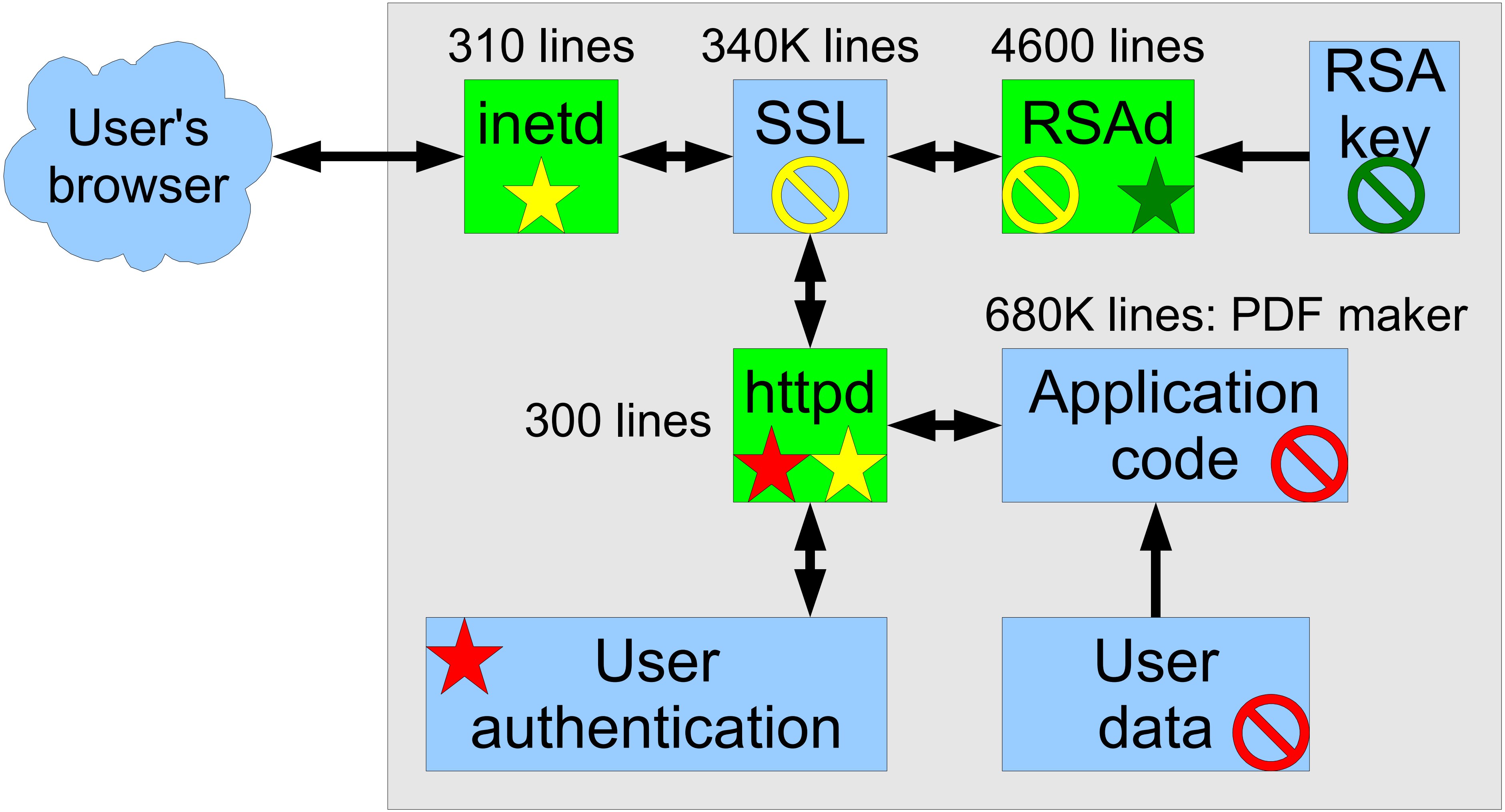
HiStar SSL Web Server

- httpd trusted with user's privilege, credentials



HiStar SSL Web Server

- Application code cannot disclose user data



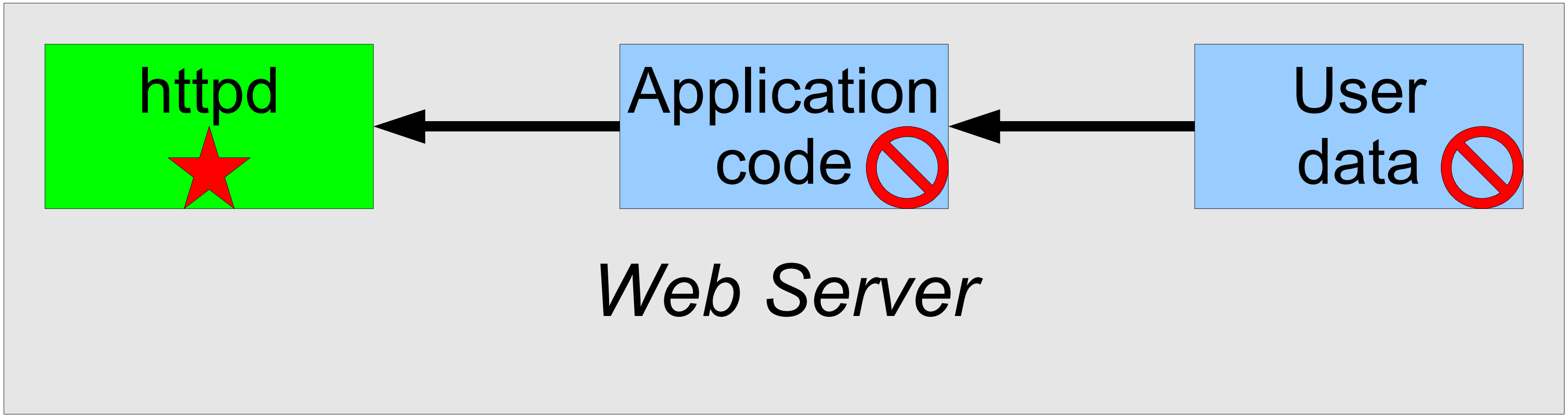
HiStar allows developers to reduce trusted code

- 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

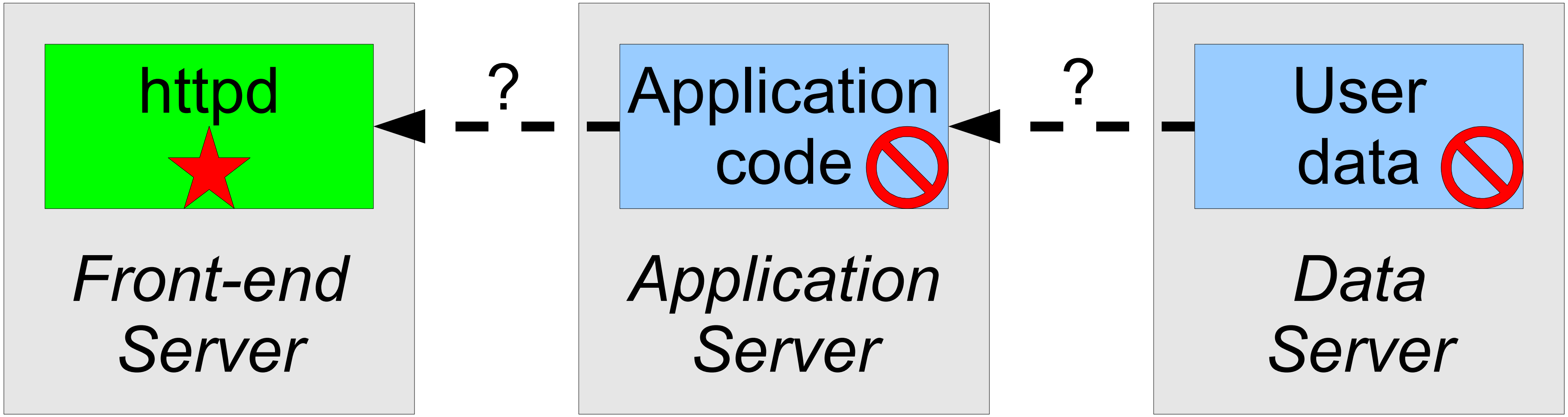
HiStar controls one machine

- Can enforce security for small web server



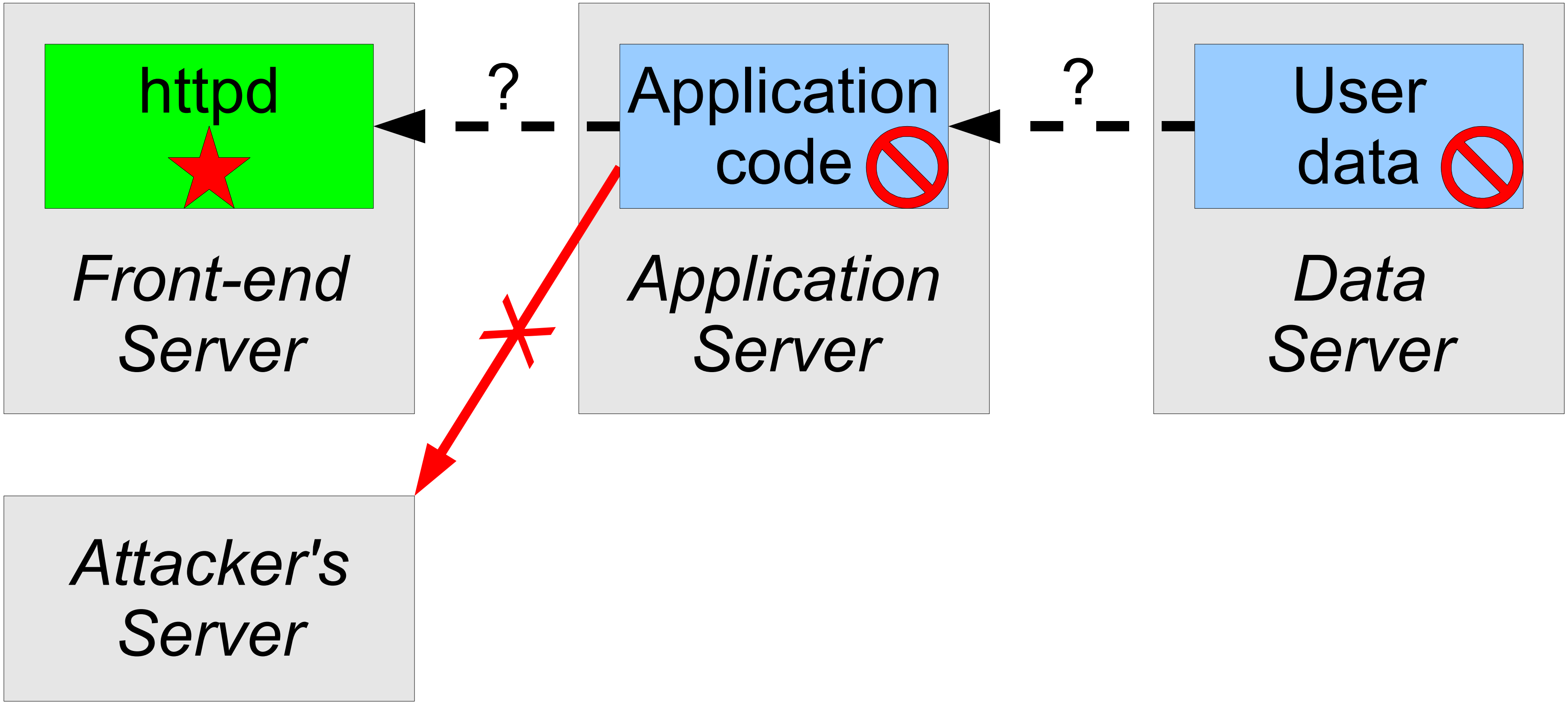
Large services are distributed

- Must use multiple machines for scalability
  - Tainted processes cannot use network in HiStar



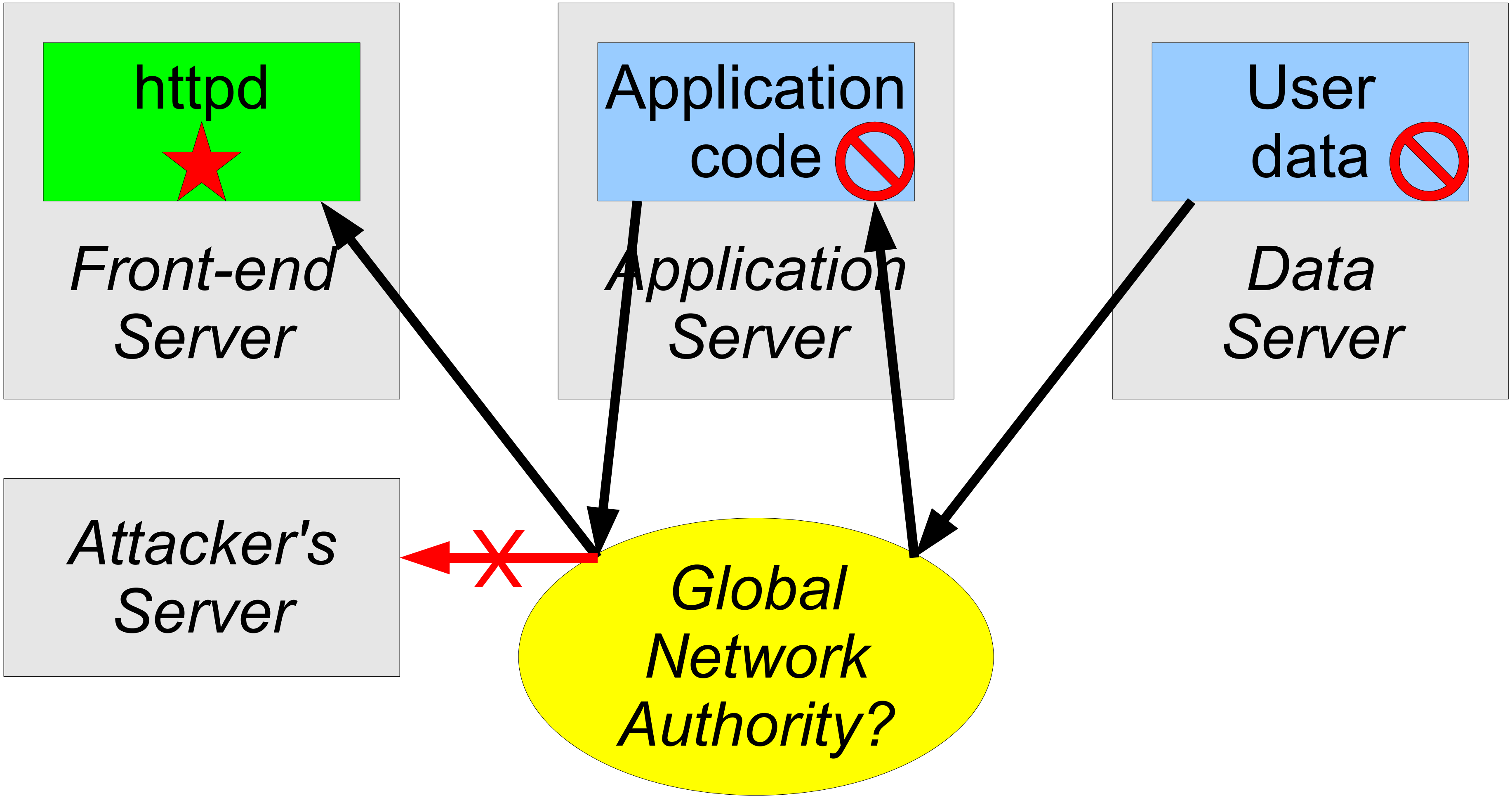
Problem: Who can we trust?

- No single fully-trusted kernel to make decisions



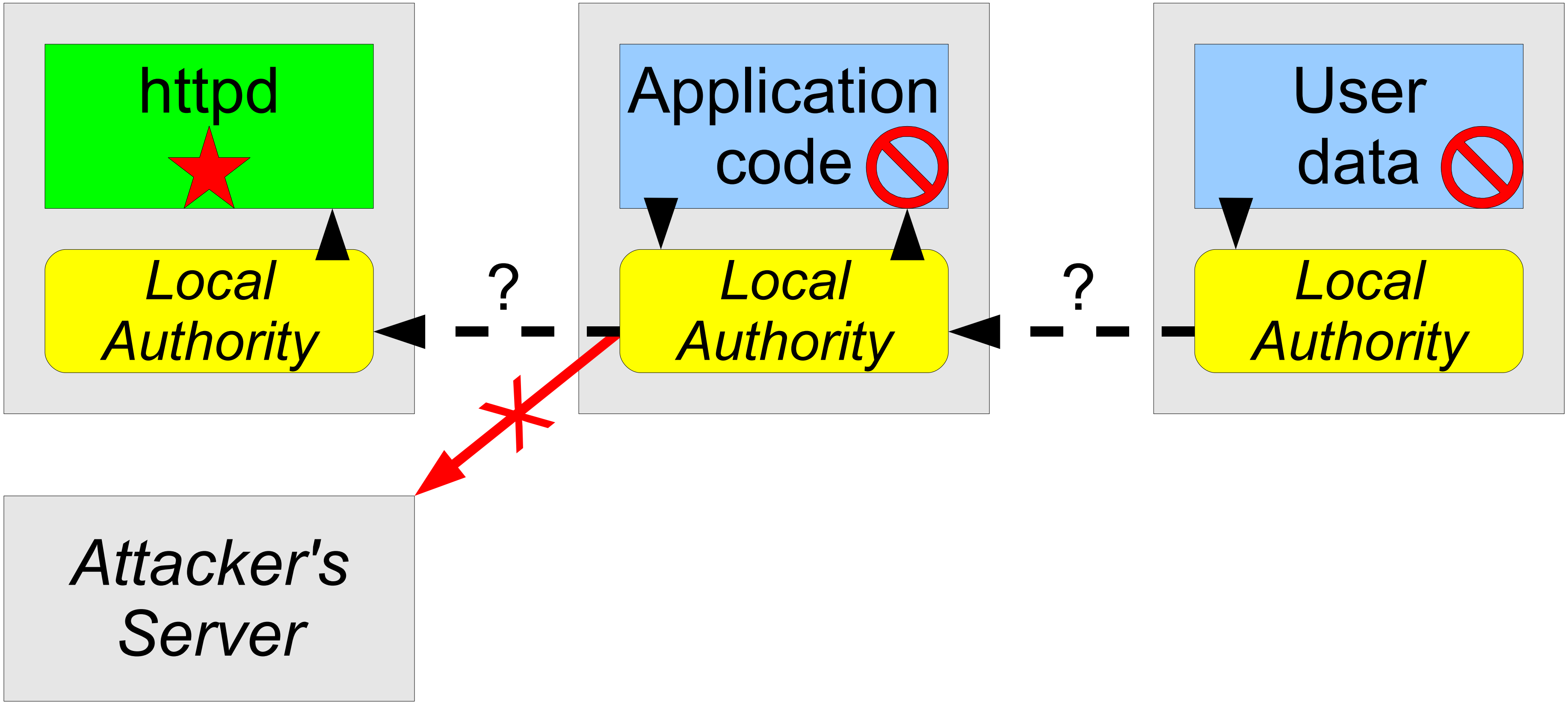
Globally-trusted authority?

- 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: Self-authenticating categories

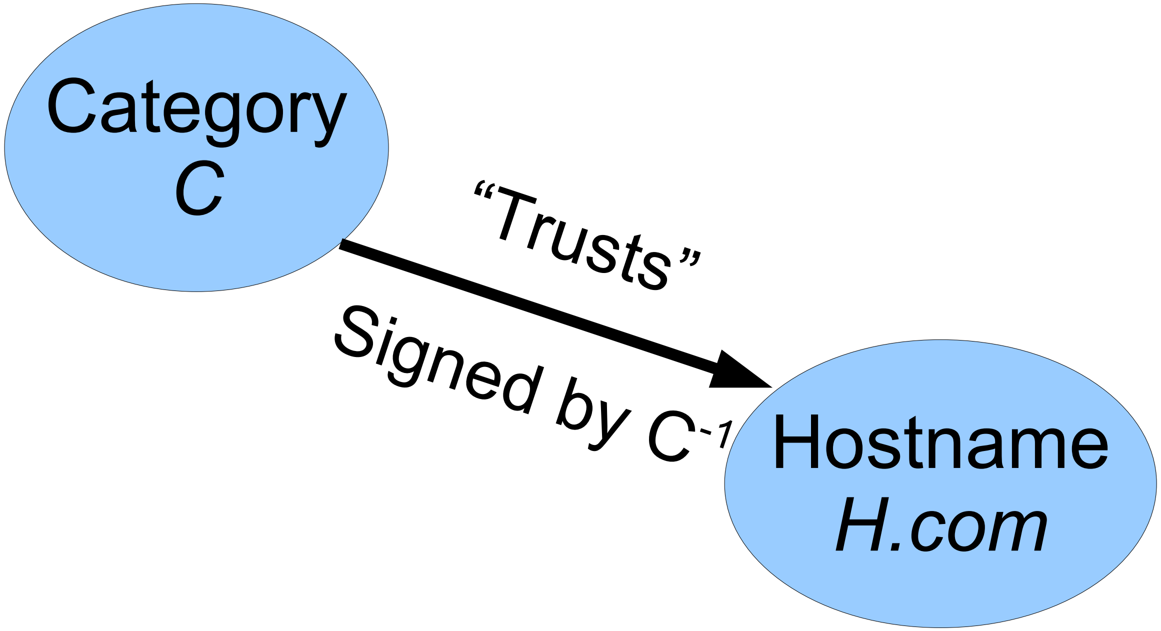
- Category (taint color) is a public key *C*

- If you know private key C^{-1}, you own (“star”) *C*

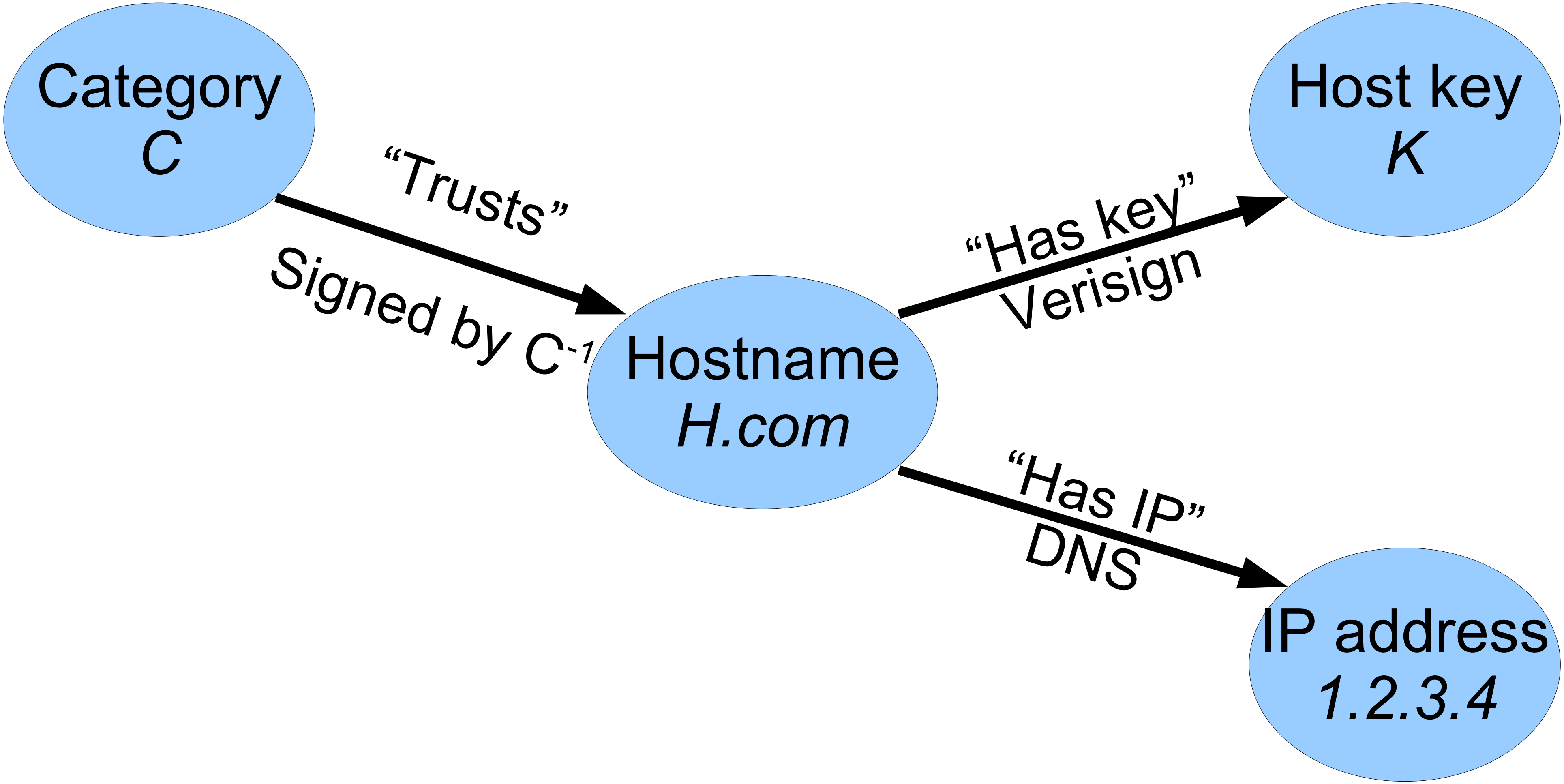
- To trust host *H* with your secret data, sign delegation (*H* is trusted to handle *C*) using C^{-1}

- Category can *“speak for itself”*

Naming machines: Strawman

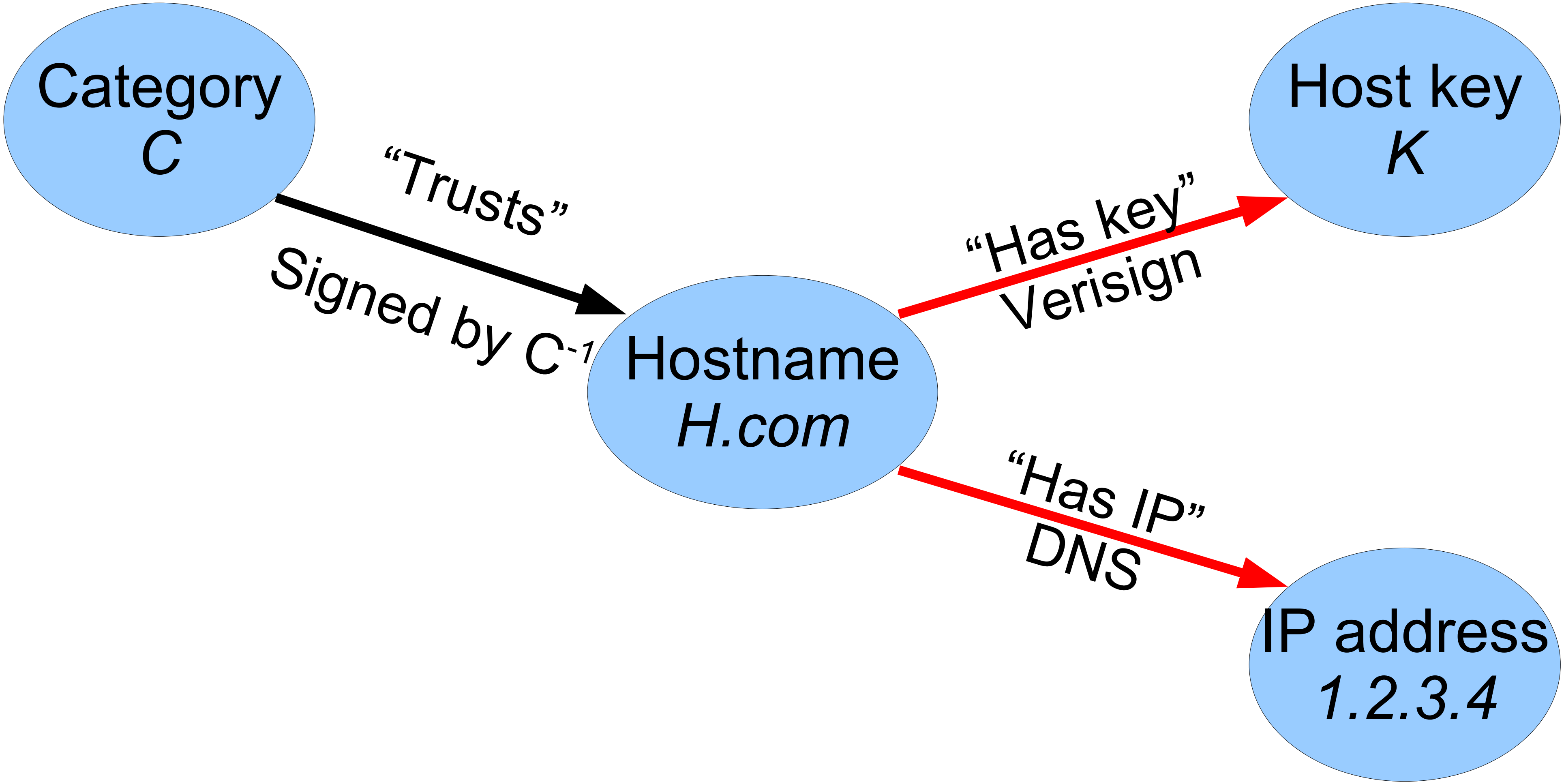


Naming machines: Strawman



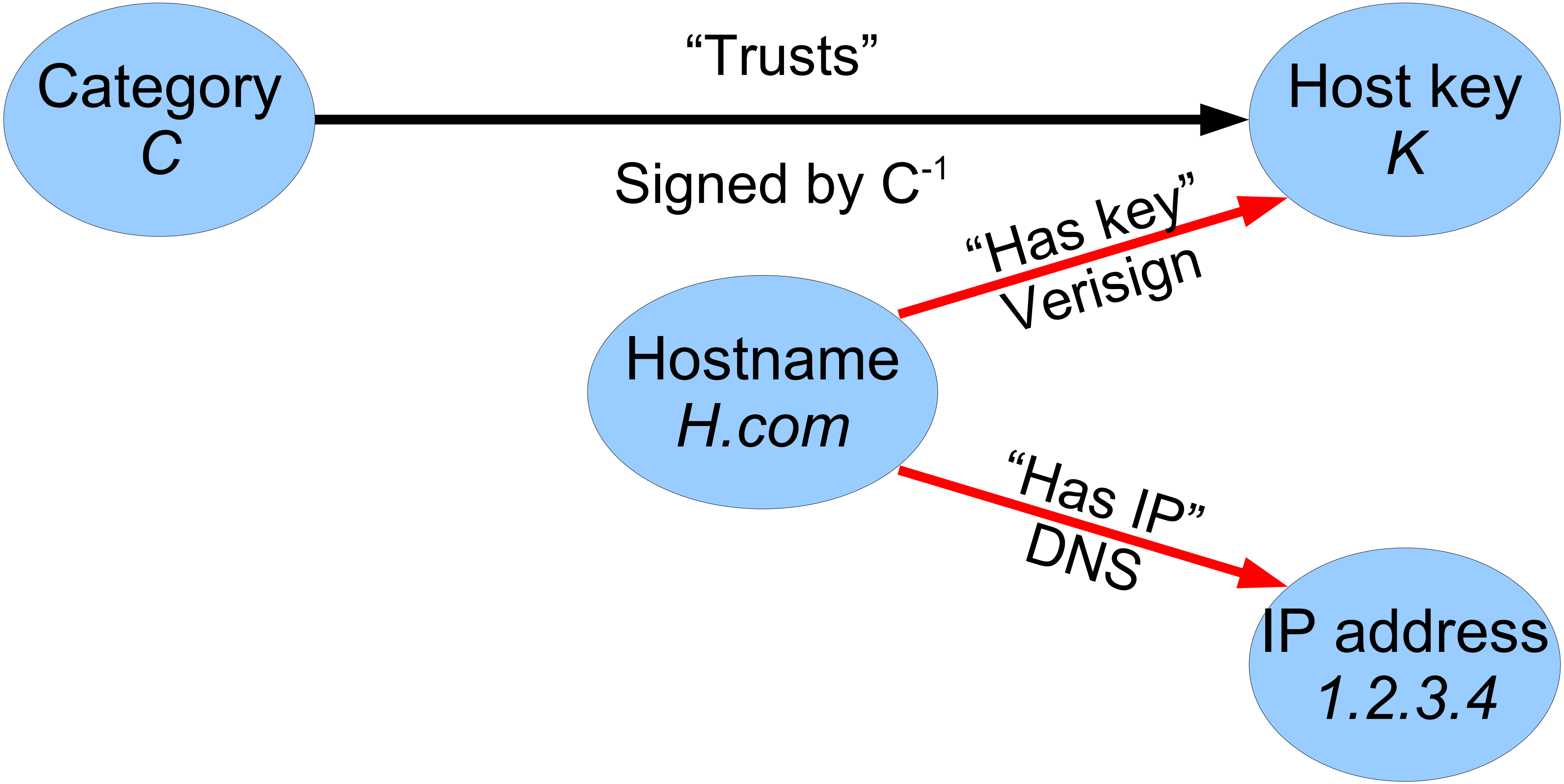
Naming machines: Strawman

- Can we reduce trust of Verisign, DNS?



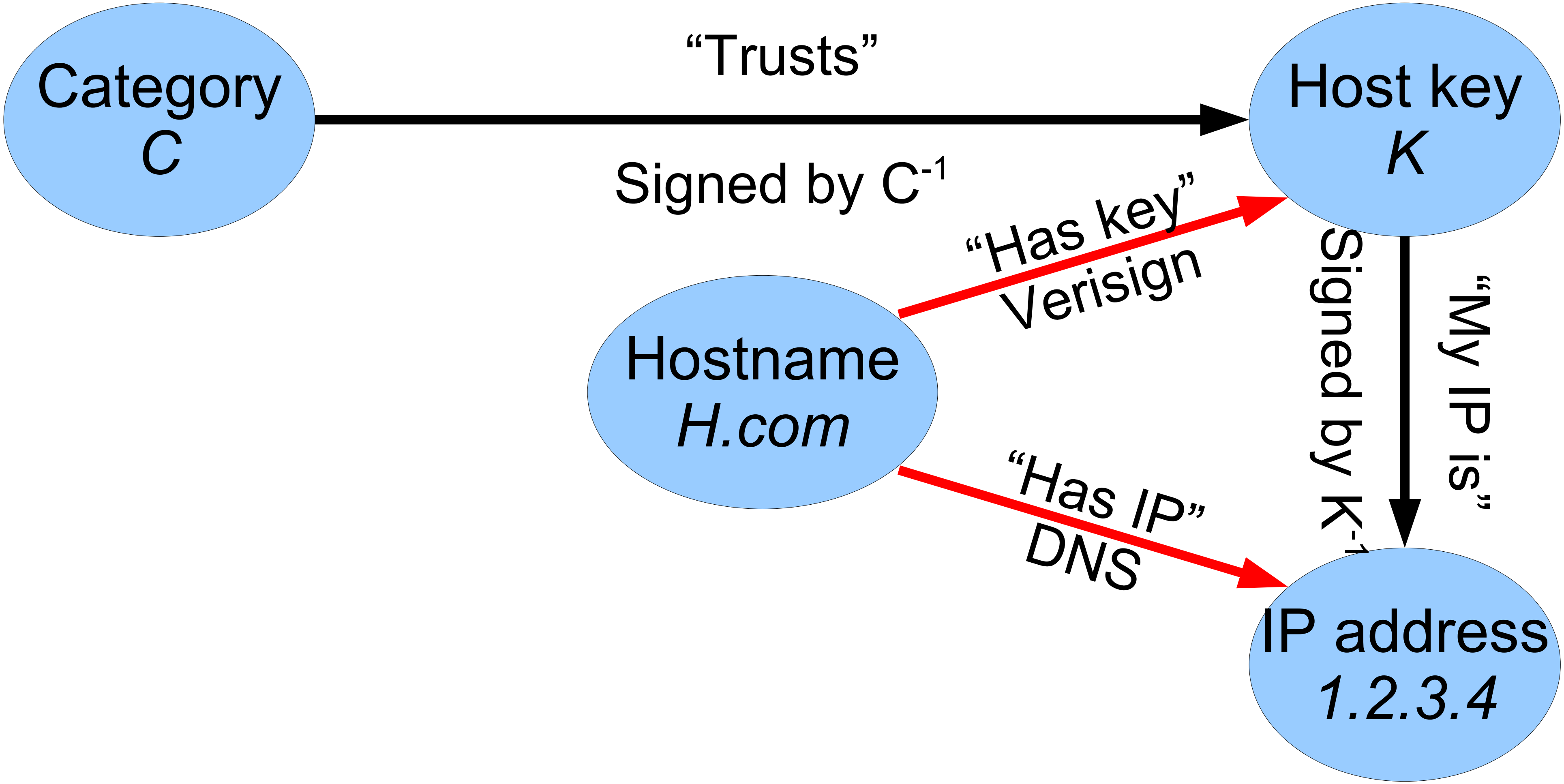
Name hosts by public key

- Trust the public key instead of the hostname!



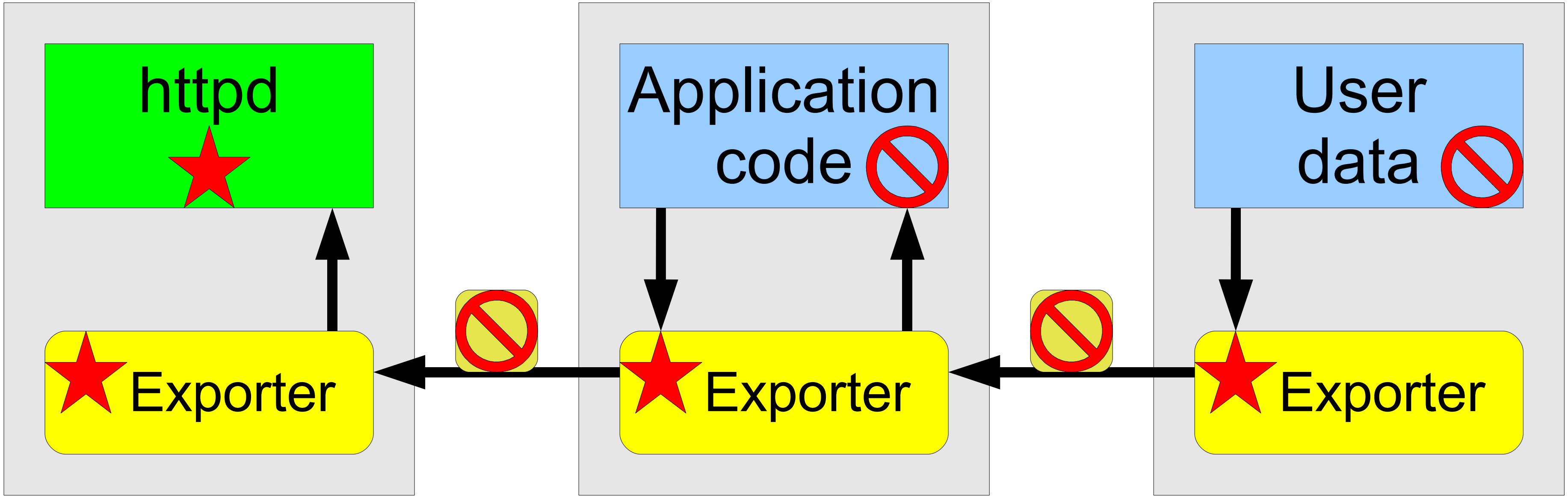
Hosts sign their IP address

- Design separates trust from distribution, policy



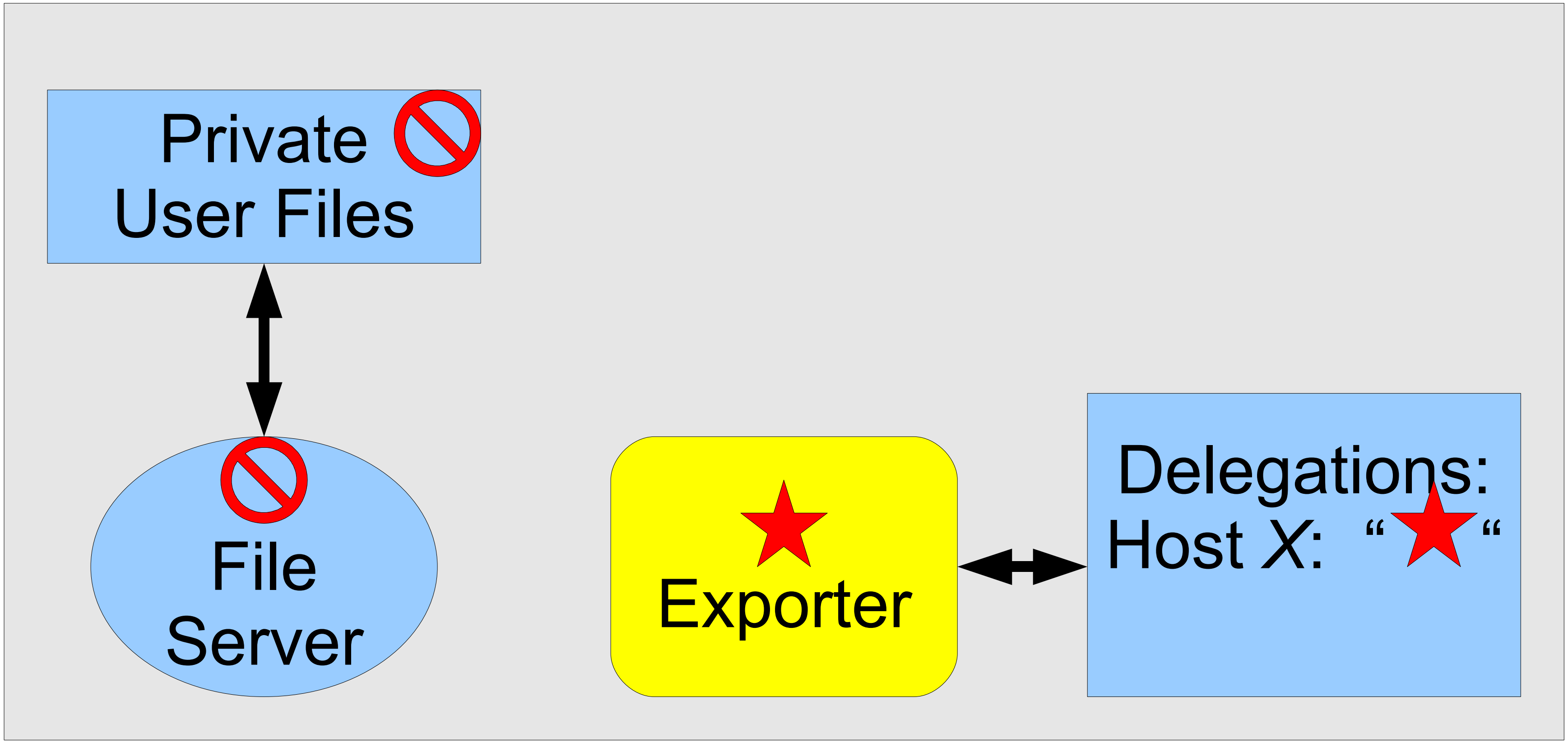
Exporter daemons

- 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



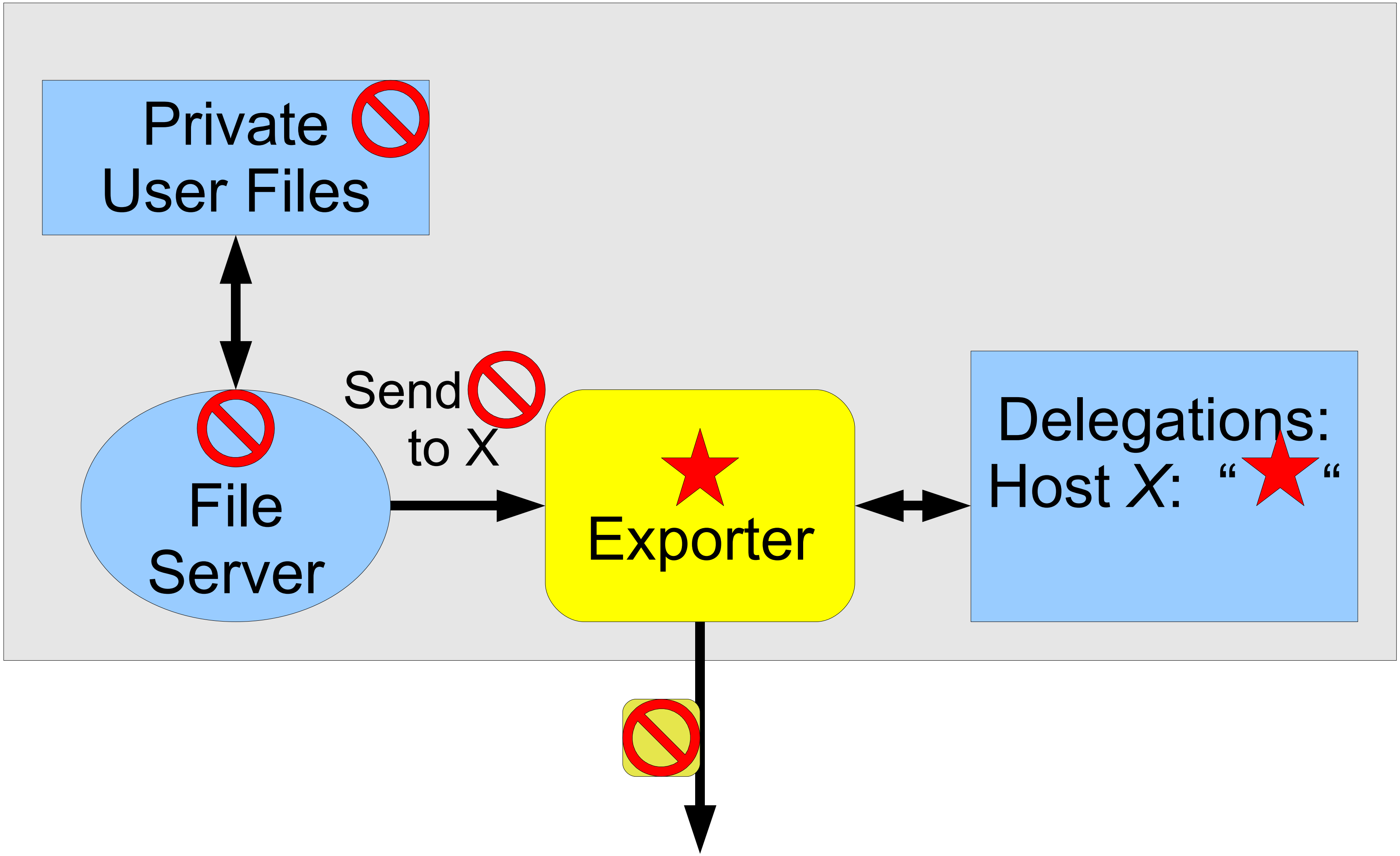
Strawman:
Exporter stores delegations

- Delegation: User trusts host X with his data

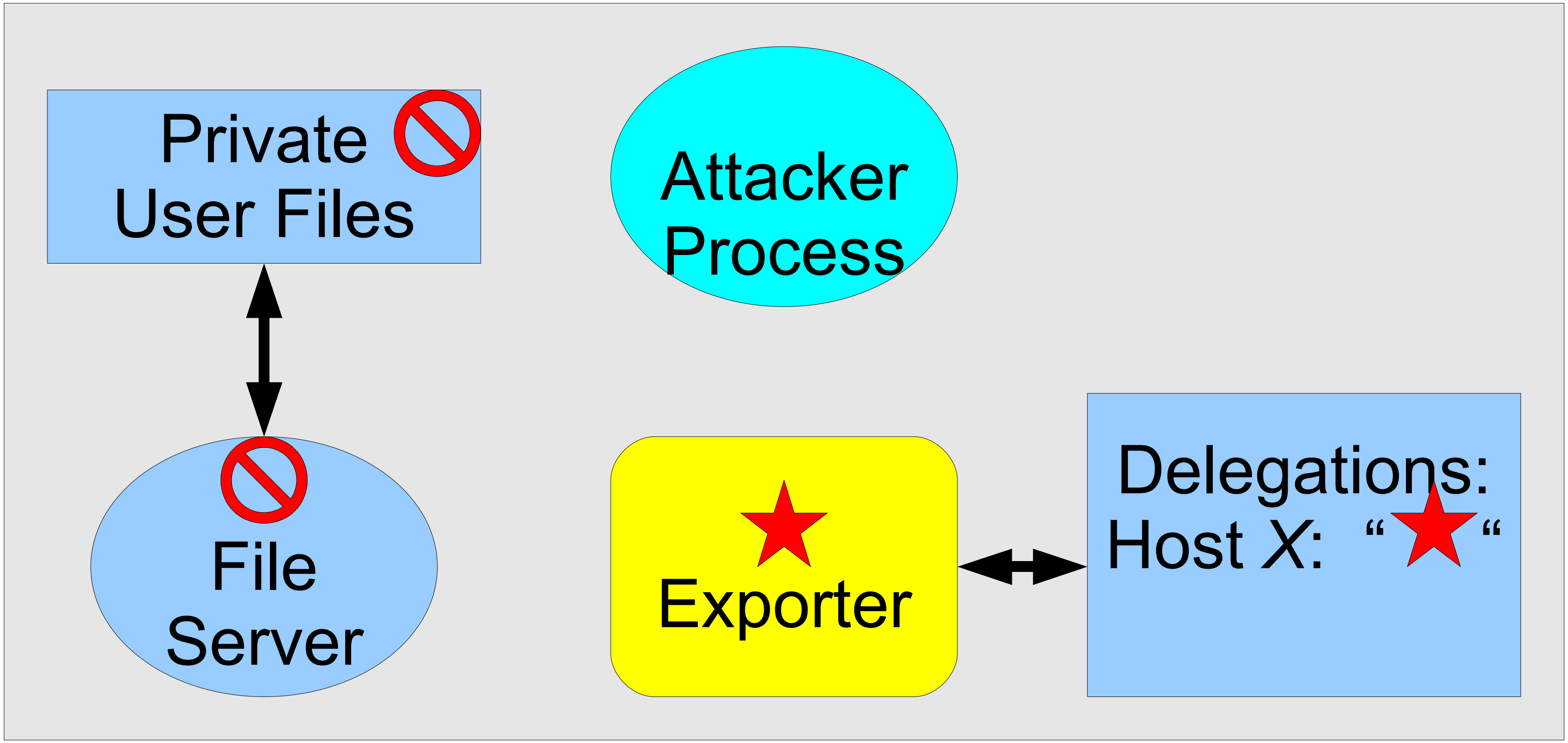


Strawman:
Exporter stores delegations

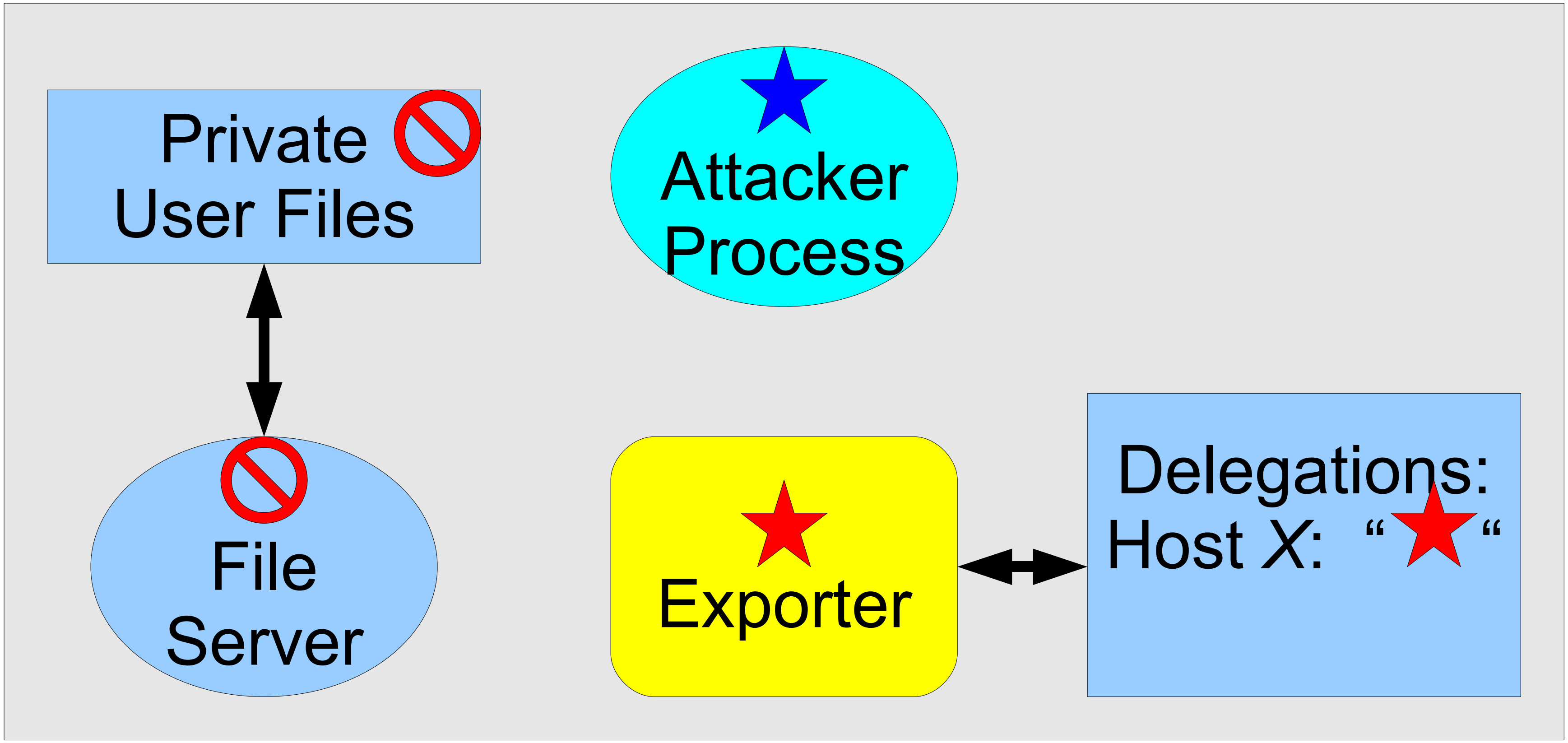
- Delegation: User trusts host X with his data



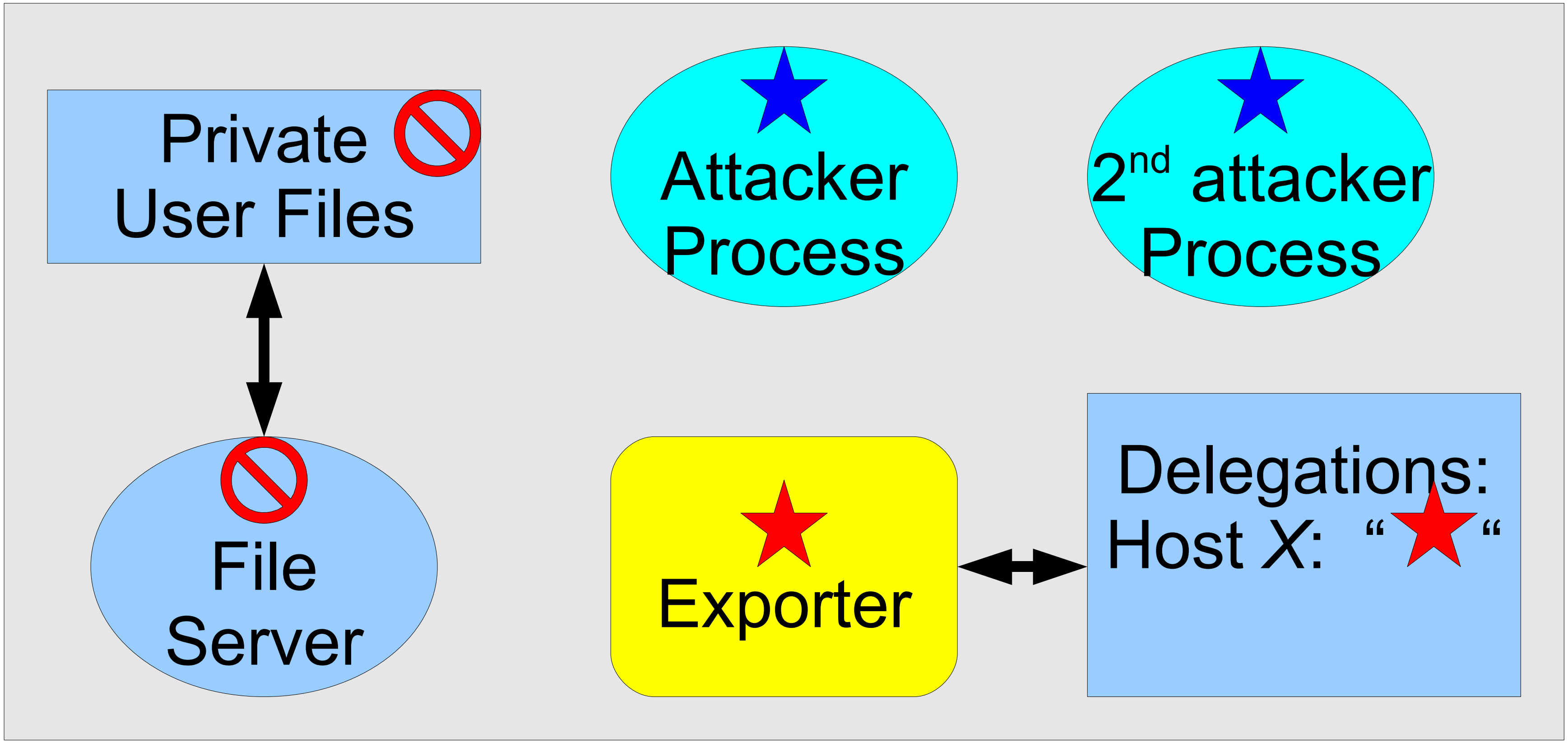
Strawman has covert channel



Strawman has covert channel



Strawman has covert channel



Private User Files 🚫

Attacker Process ★

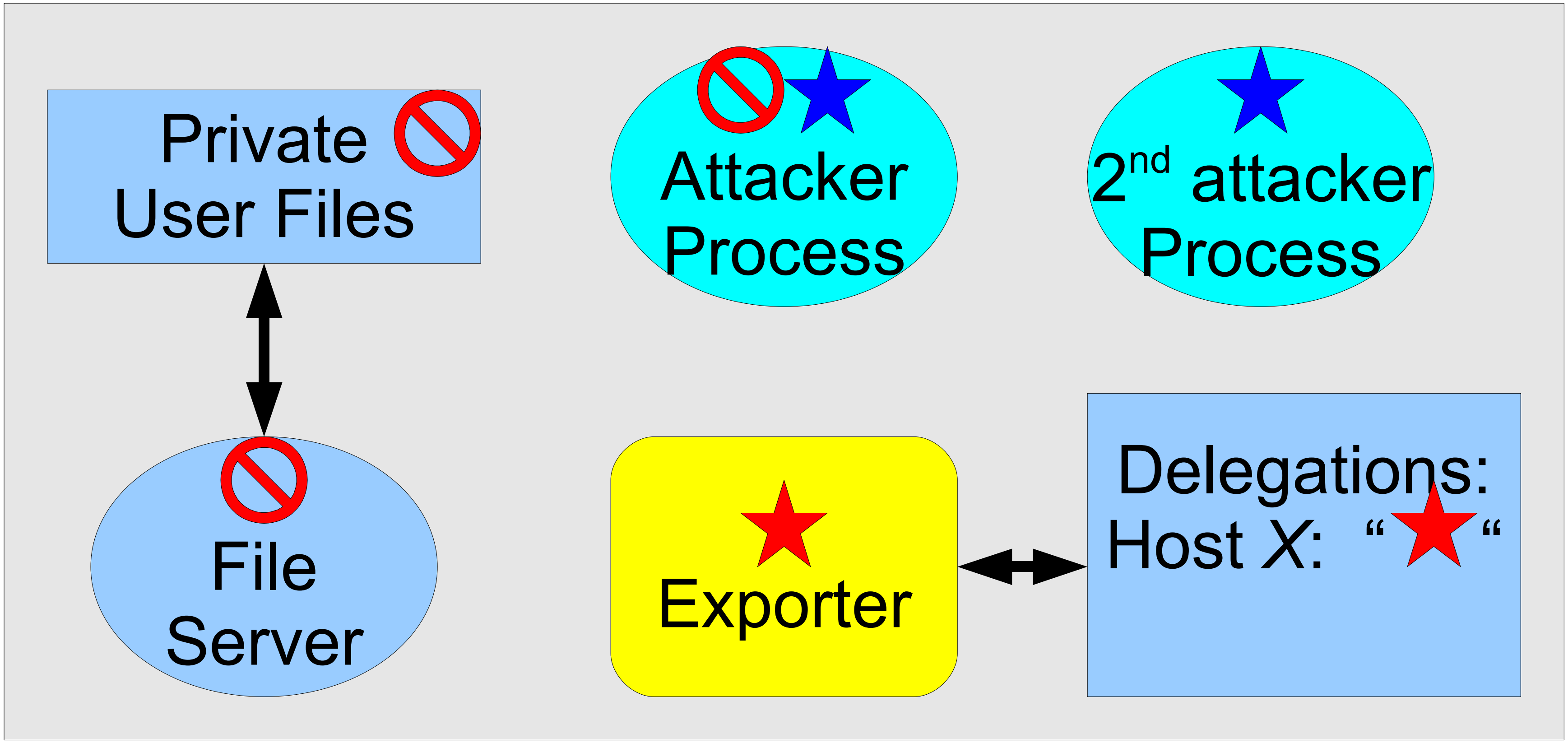
2nd attacker Process ★

🚫 File Server

★ Exporter

Delegations:
Host *X*: "★"

Strawman has covert channel



Private User Files

Attacker Process

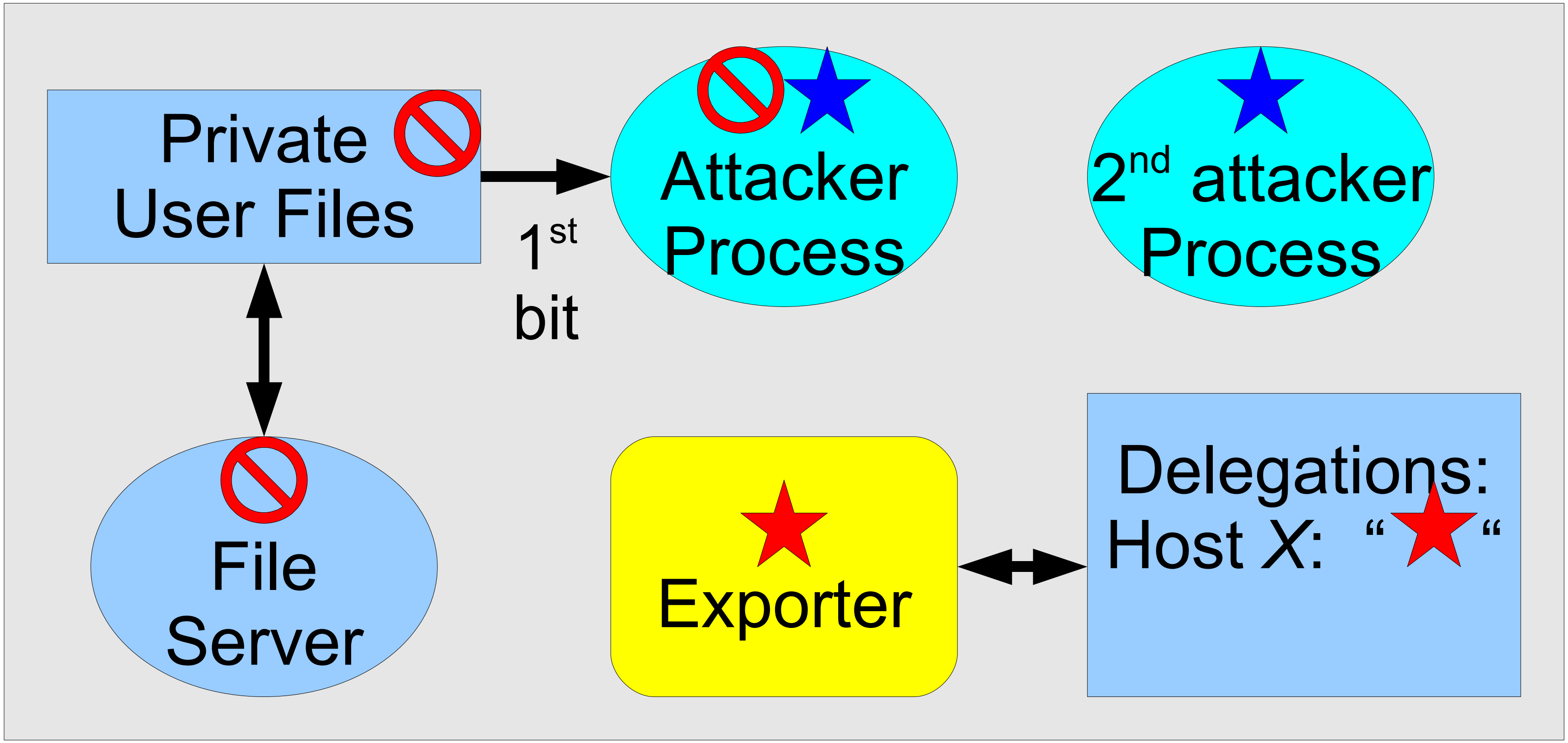
2nd attacker Process

File Server

Exporter

Delegations:
Host *X*: "★"

Strawman has covert channel



Private User Files

1st bit

Attacker Process

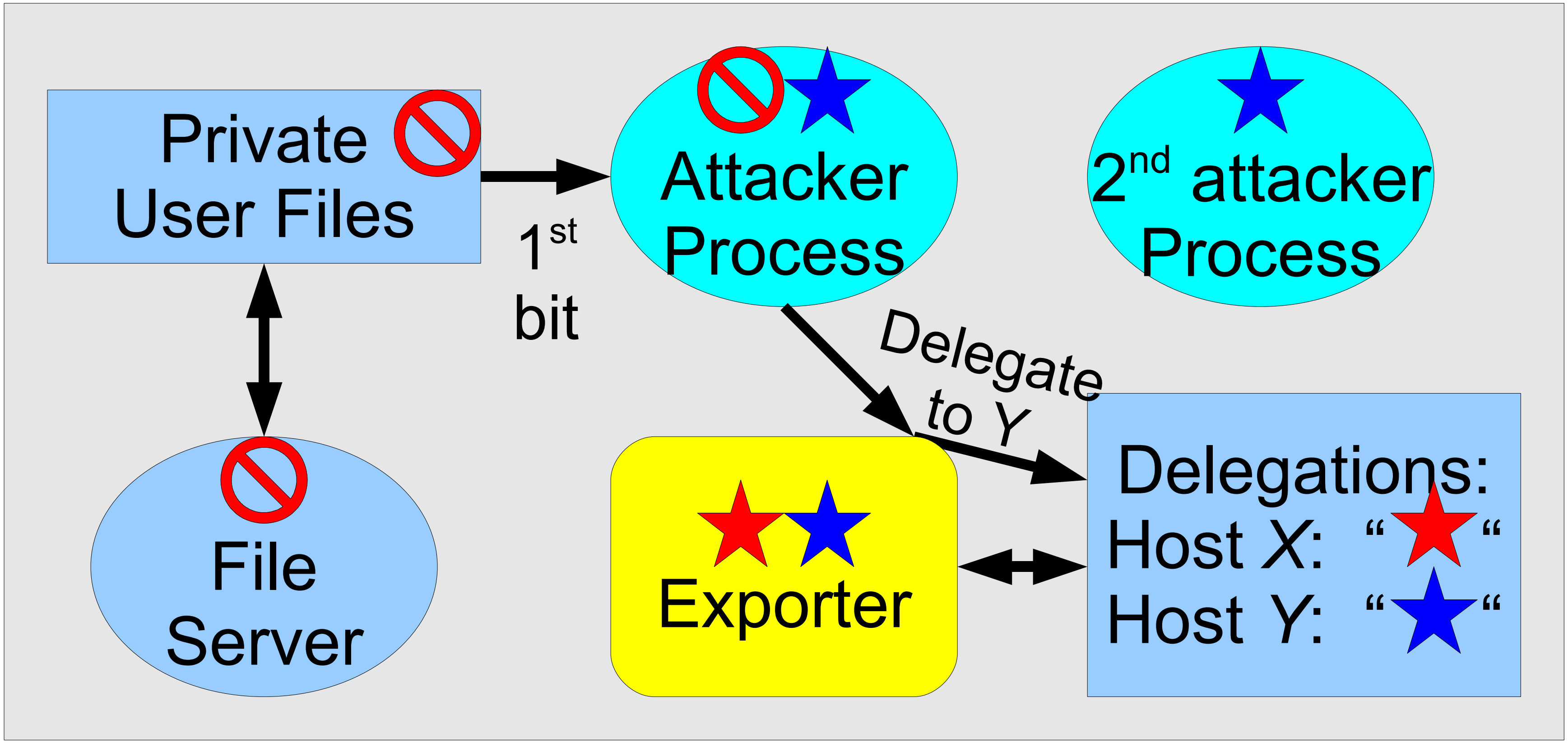
2nd attacker Process

File Server

Exporter

Delegations: Host *X*: “ ★ “

Strawman has covert channel



Private User Files

1st bit

Attacker Process

2nd attacker Process

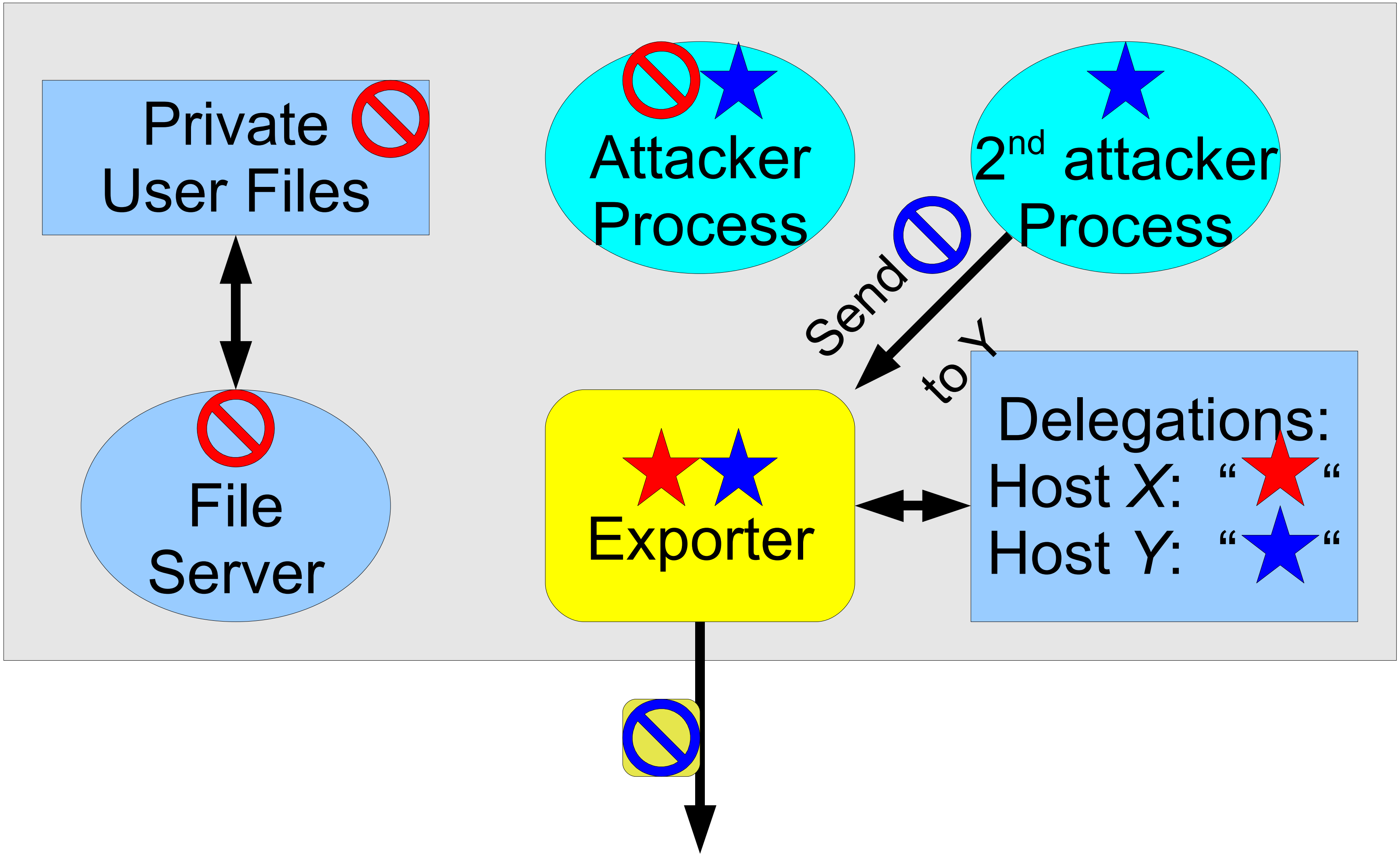
Delegate to Y

File Server

Exporter

Delegations:
Host *X*: "★"
Host *Y*: "★"

Strawman has covert channel



Private User Files

File Server

Attacker Process

2nd attacker Process

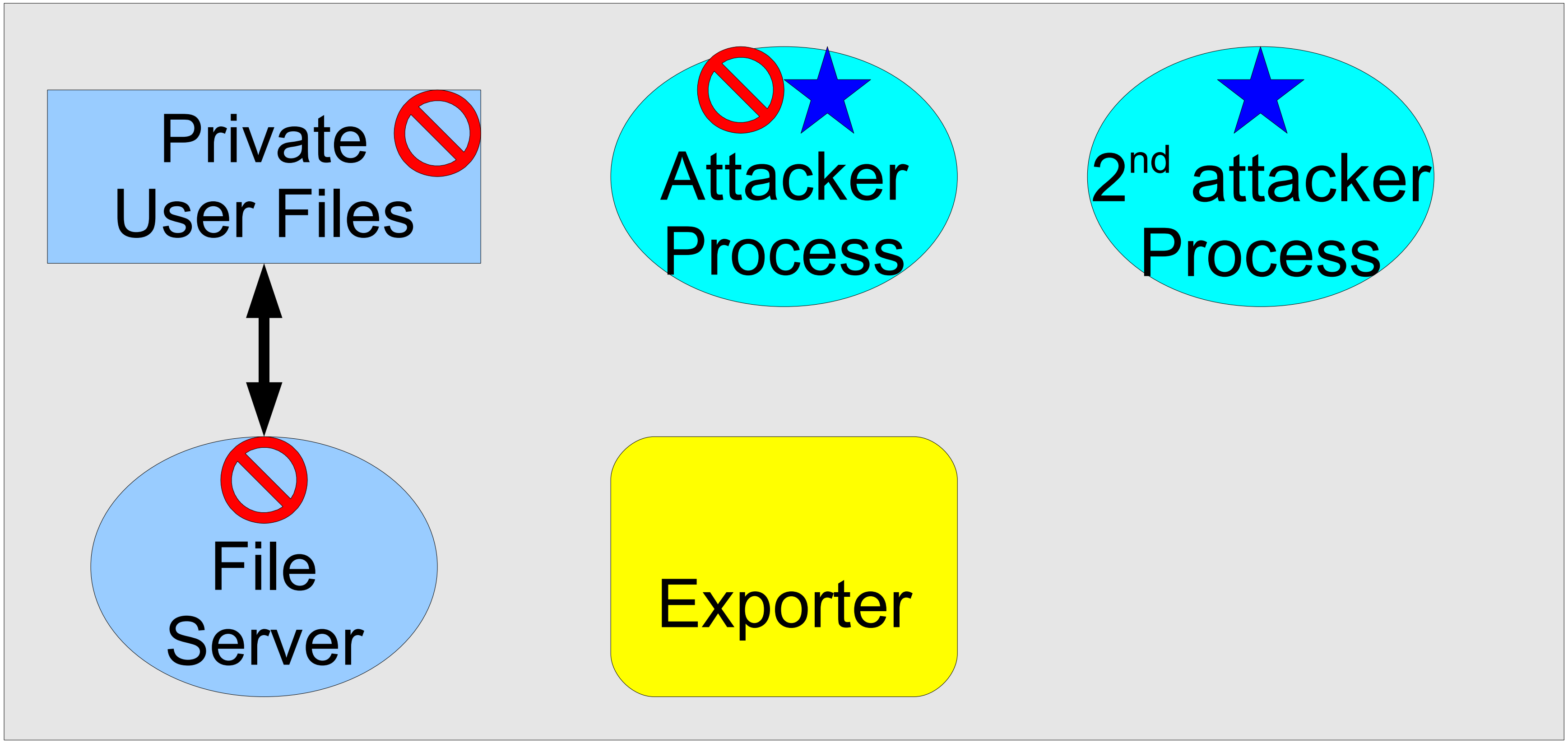
Send to Y

Exporter

Delegations:
Host *X*: "★"
Host *Y*: "★"

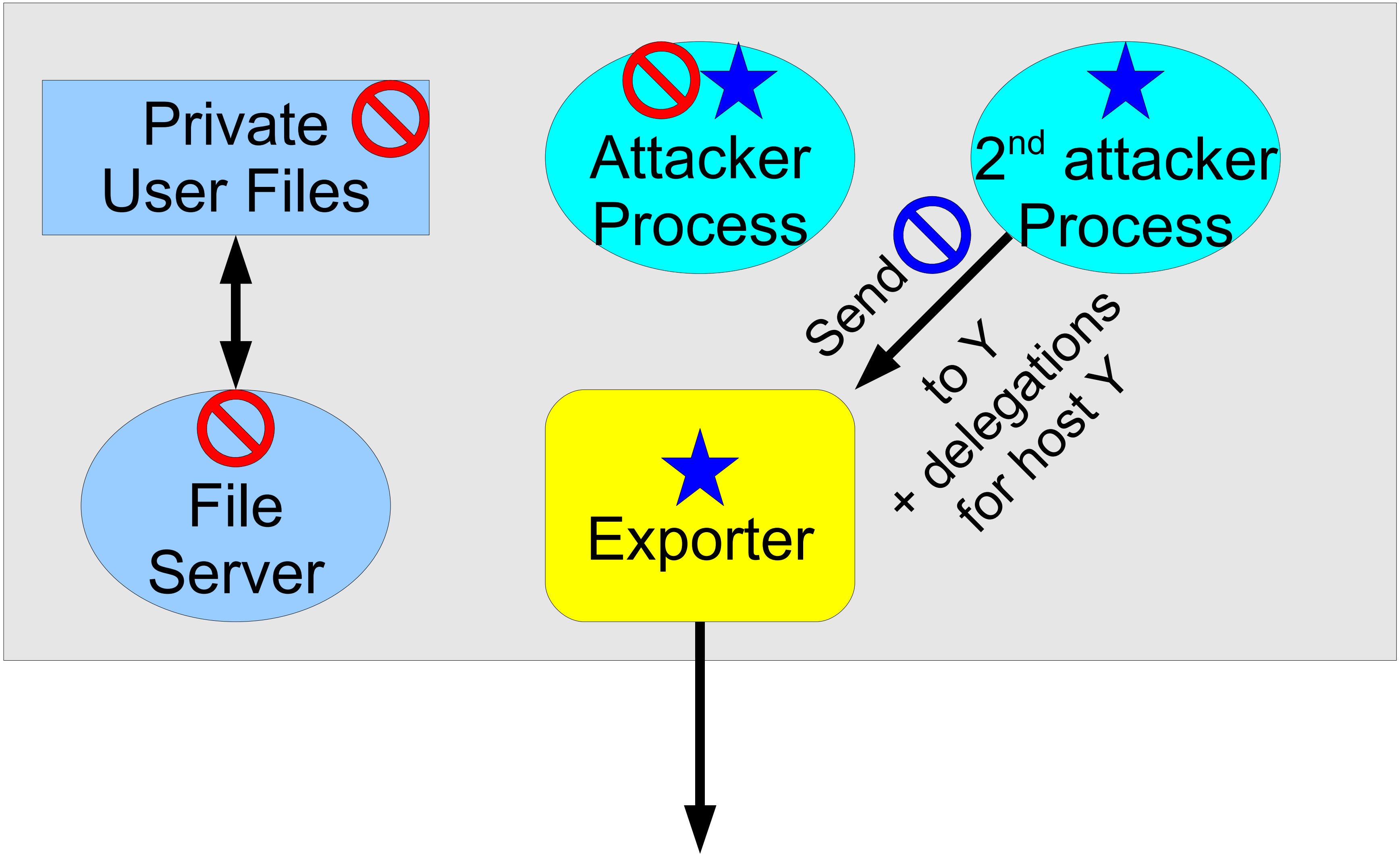
Solution: Stateless exporter

- Delegations are self-authenticating



Sender supplies delegations

- Result only depends on sender-supplied data



Exporter's interface

-
  ```
  void send(ip_address, tcp_port,
            wire_message, delegation_set)
  ```

-
  ```
  struct wire_message {
      pubkey         recipient_exporter;
      slot           recipient_slot;
      category_set   label;
      category_set   grant_ownership;
      delegation_set dset;
      opaque         data;
  };
  ```

Exporter's interface

-
  ```
  void send(ip_address, tcp_port,
            wire_message, delegation_set)
  ```

-
  ```
  struct wire_message {
      pubkey         recipient_expor
      slot           recipient_sl
      category_set   label;
      category_set   grant_owner
      delegation_set dset;
      opaque         data;
  };
  ```

Convince sending exporter it's safe to send message:

Category delegations + Address delegation
(secrecy)

Exporter's interface

-
```
void send(ip_address, tcp_port,
          wire_message, delegation_set)
```

-
```
struct wire_message {
    pubkey         recipient_exporter;
    slot           recipient_slot;
    category_set   label;
    category_set   grant_ownership;
    delegation_set dset;
    opaque         data;
};
```

Convince recipient exporter
it's safe to accept message:

Category delegations
(integrity)

RPC using exporter messages

- Much like RPC over UDP
  - Allocate resources to receive the reply
  - Send the request
  - Wait for reply message to arrive
  - Periodically retransmit or time out

- RPC library manages delegations
  - Untrusted by OS, exporters

Security details

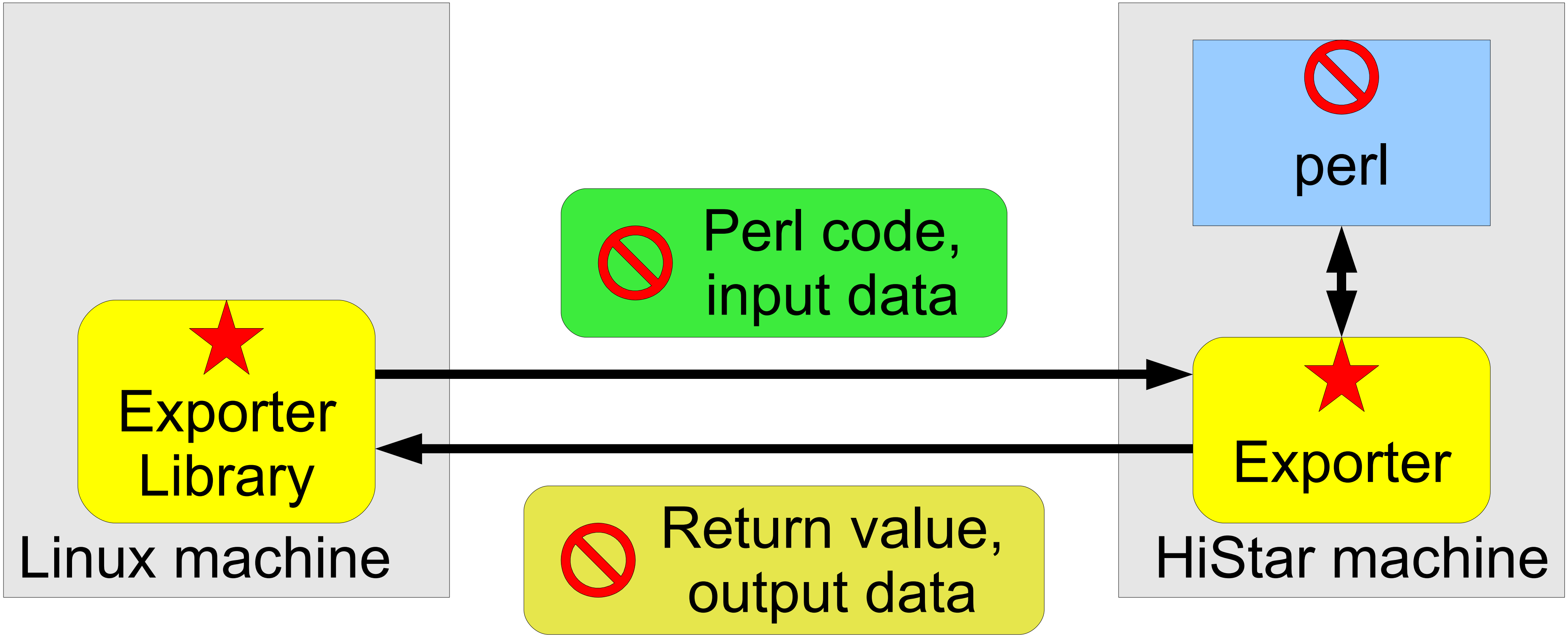
- All messages encrypted+MAC on the network
  - Session keys between each pair of exporters

- Ownership and address delegations expire
  - Compromised machine only affects recent users
  - Exporters periodically broadcast address delegations

- Trusted exporter: 3,700 lines of C++ (plus libs)
  - Enforces policy on arbitrary untrusted code

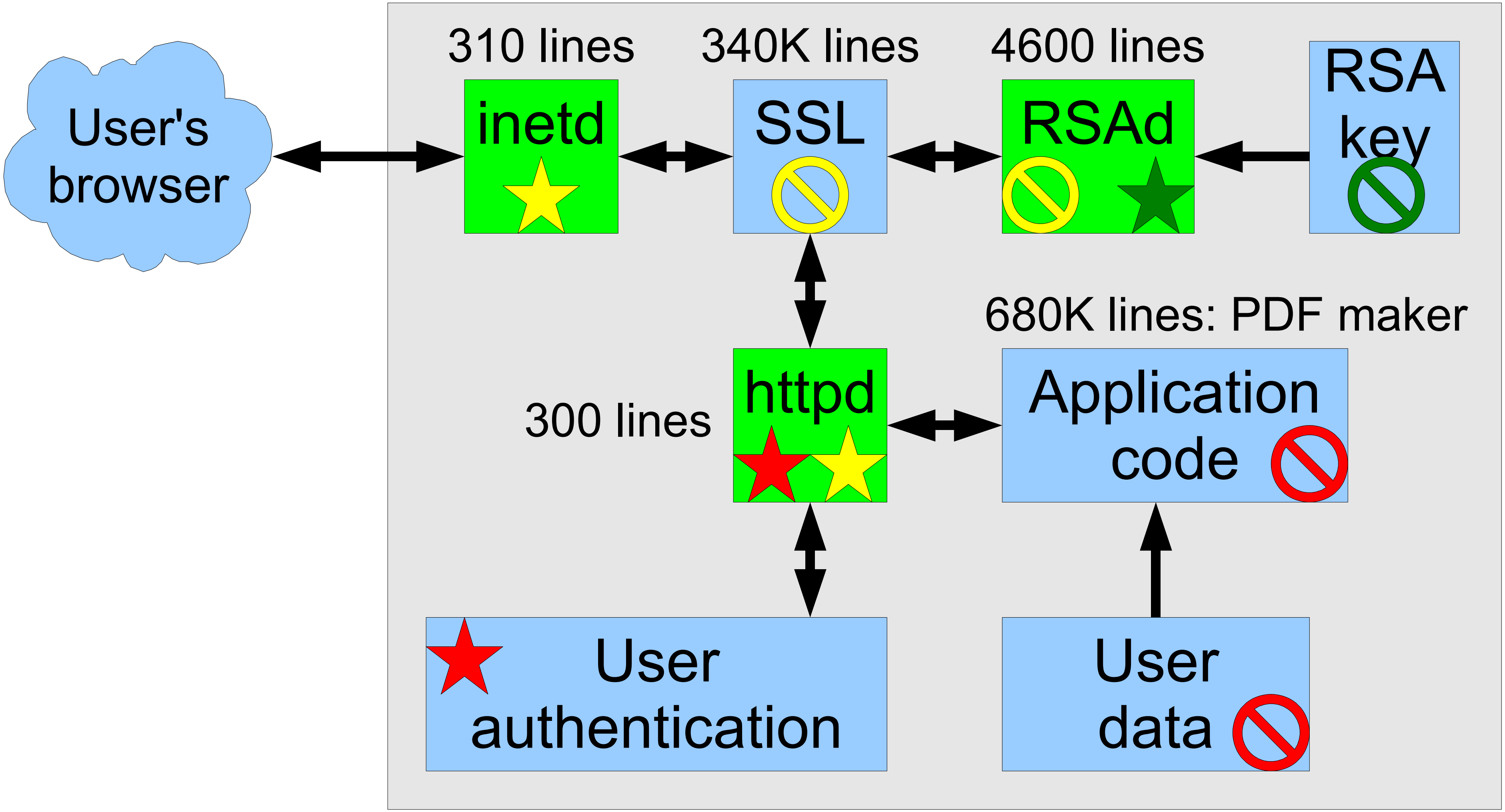
Incremental deployment

- Run untrusted perl code on HiStar, from Linux
  - Well-defined security properties specified by label



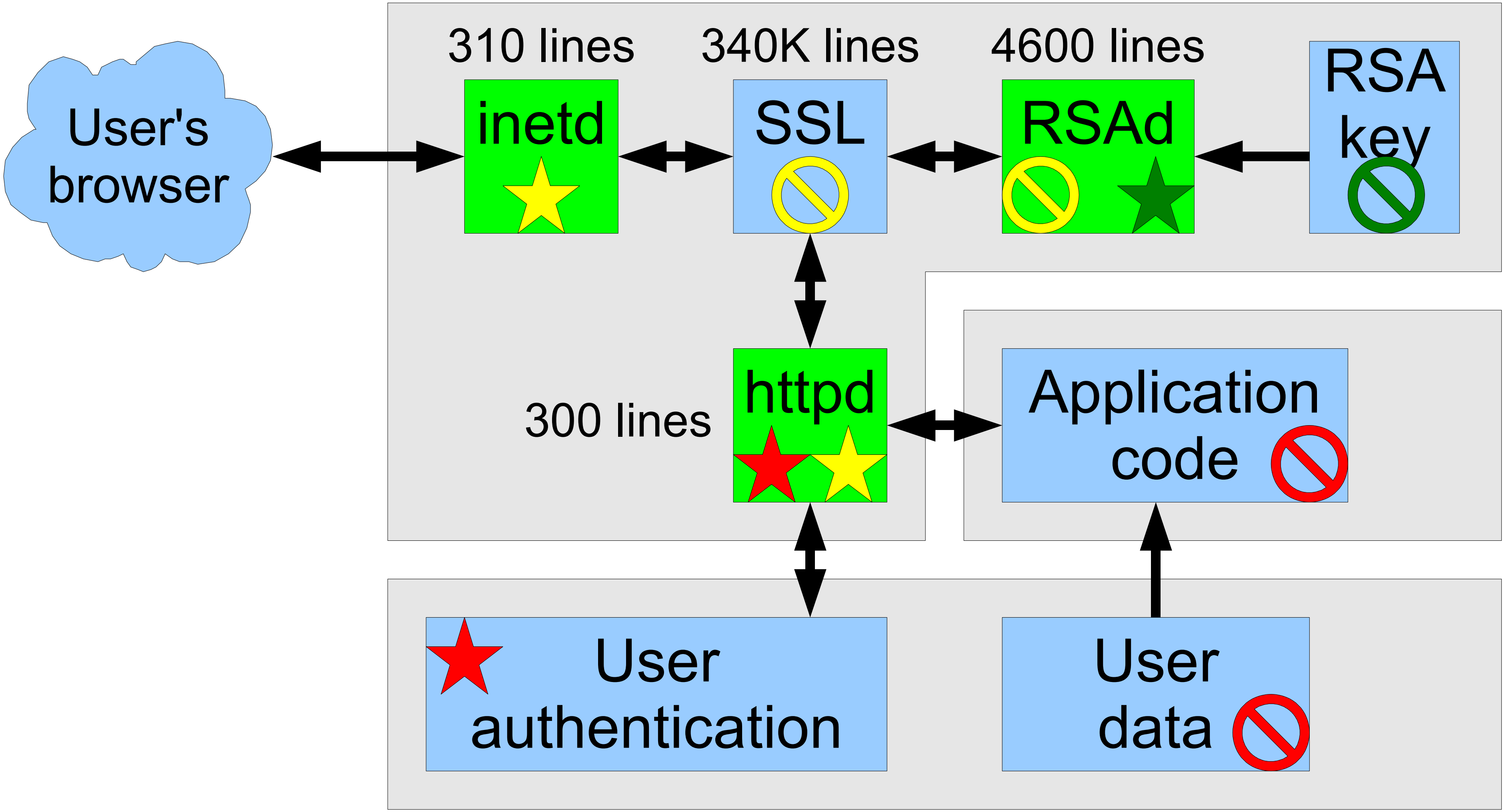
Recall: HiStar SSL Web Server

- Only small fraction of code (green) is trusted



Scalable, Distributed Web Server

- Same security properties (but trust exporters)



Conclusion

- Shown how to reduce amount of trusted code
  - Trusted: 20,000 line kernel + 3,700 line exporter
  - Enforce security of arbitrary distributed application
- Explicit information flow removes covert channels
  - Even root privileges can be made explicit
- No need for globally-trusted authority
  - Self-authenticating categories make trust explicit

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

Limitations

- Hard to enforce correctness, progress
  - Malicious code cannot leak your data
  - But if you give it write access, it can corrupt it!
- Applicable to servers, not obvious for desktops
  - May need to provide trusted path to and from user
- Fine-grained isolation requires code changes
  - Code not always structured along information flow
- Covert channels are inevitable

Potential ways to reduce covert channels

- One idea: “secure” scheduler for sensitive data
  - Preempt based on instruction counts instead of time
  - Prohibit process from yielding CPU to others

- Only incur overhead for, e.g. checking password
  - Spend a deterministic 0.1 sec CPU time for login

Verifying security

- Verifying the design
  - Can objectively determine if something is safe
  - Model-checking subset of syscalls (Taral Joglekar)
    - Seems to provide non-interference

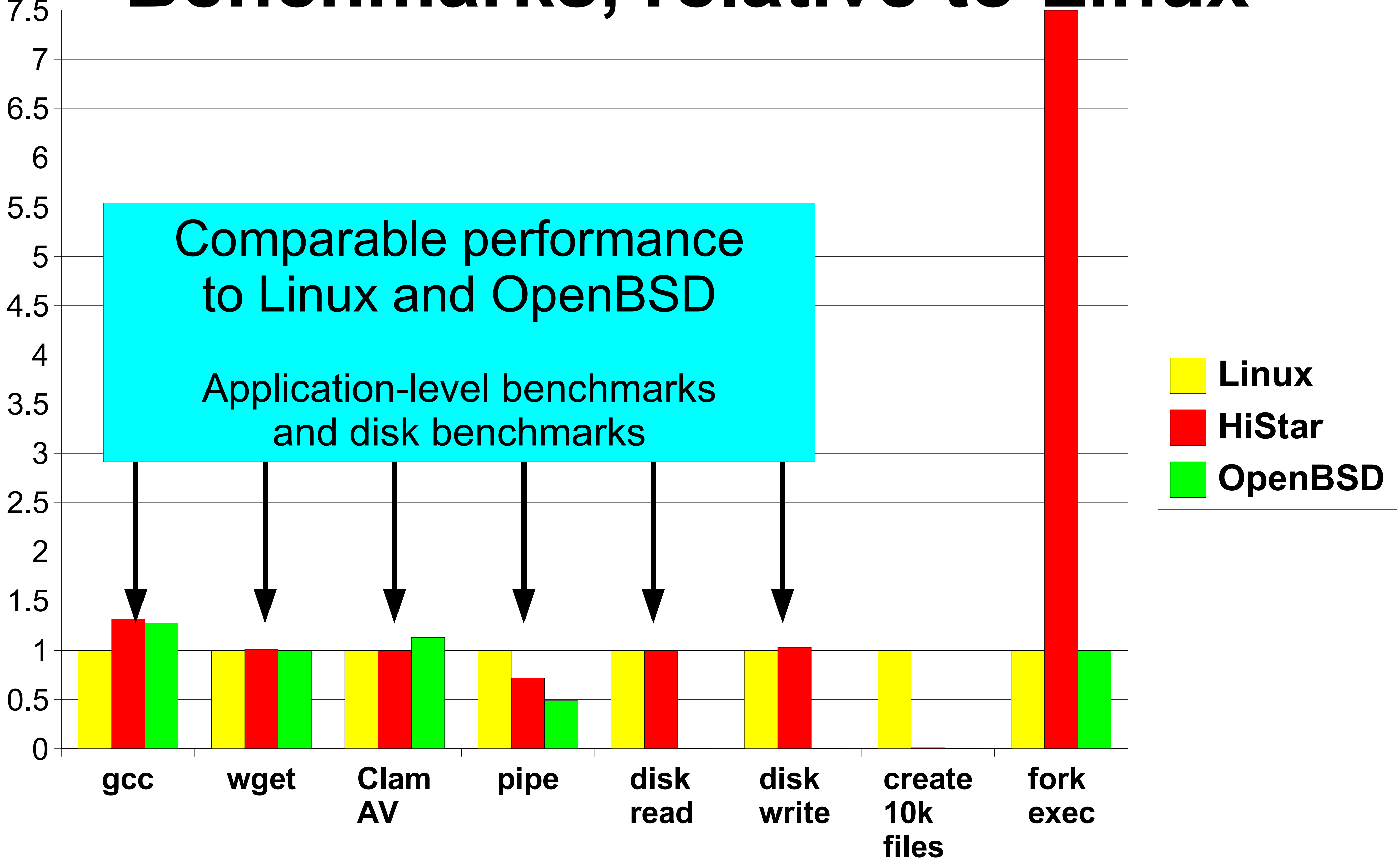
- Verifying the implementation
  - Symbolic execution (Peter Pawlowski, Daniel Dunbar)
    - Found two bugs in HiStar (and a few more in EXE)
  - Static taint analysis (Suhabe Bugrara, Peter Hawkins)
    - No user pointer derefs (where alias analysis terminates)

How to *really* reboot?

- Separate command called “`ureboot`”

- Kills all processes except itself (`ureboot`)
  - Delete containers, except for the file system
  - FS containers have special bit that excludes threads
- Start a new `init` process
  - It will start everything else (TCP/IP stack, sshd, ...)

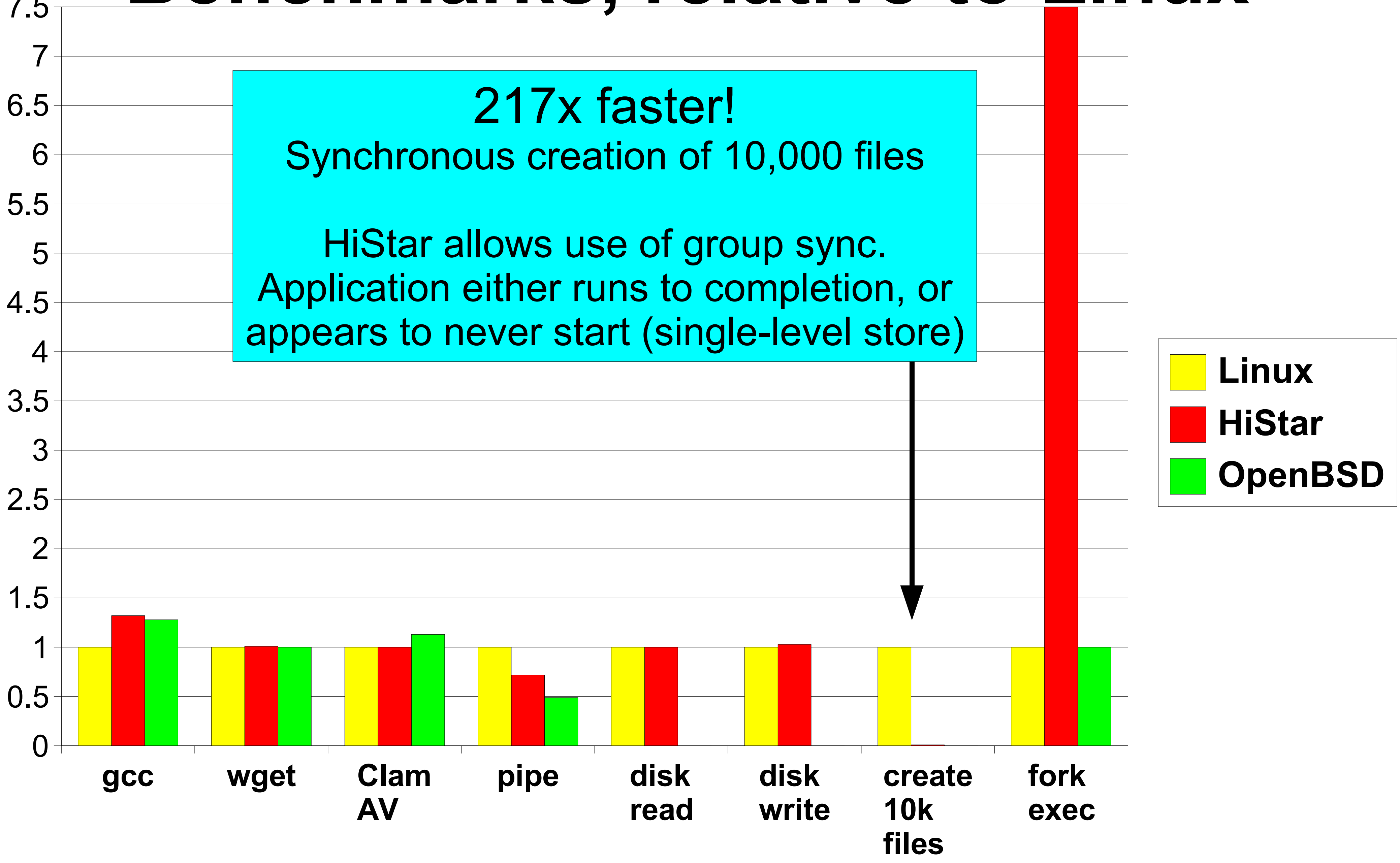
Benchmarks, relative to Linux



Comparable performance to Linux and OpenBSD

Application-level benchmarks and disk benchmarks

Benchmarks, relative to Linux

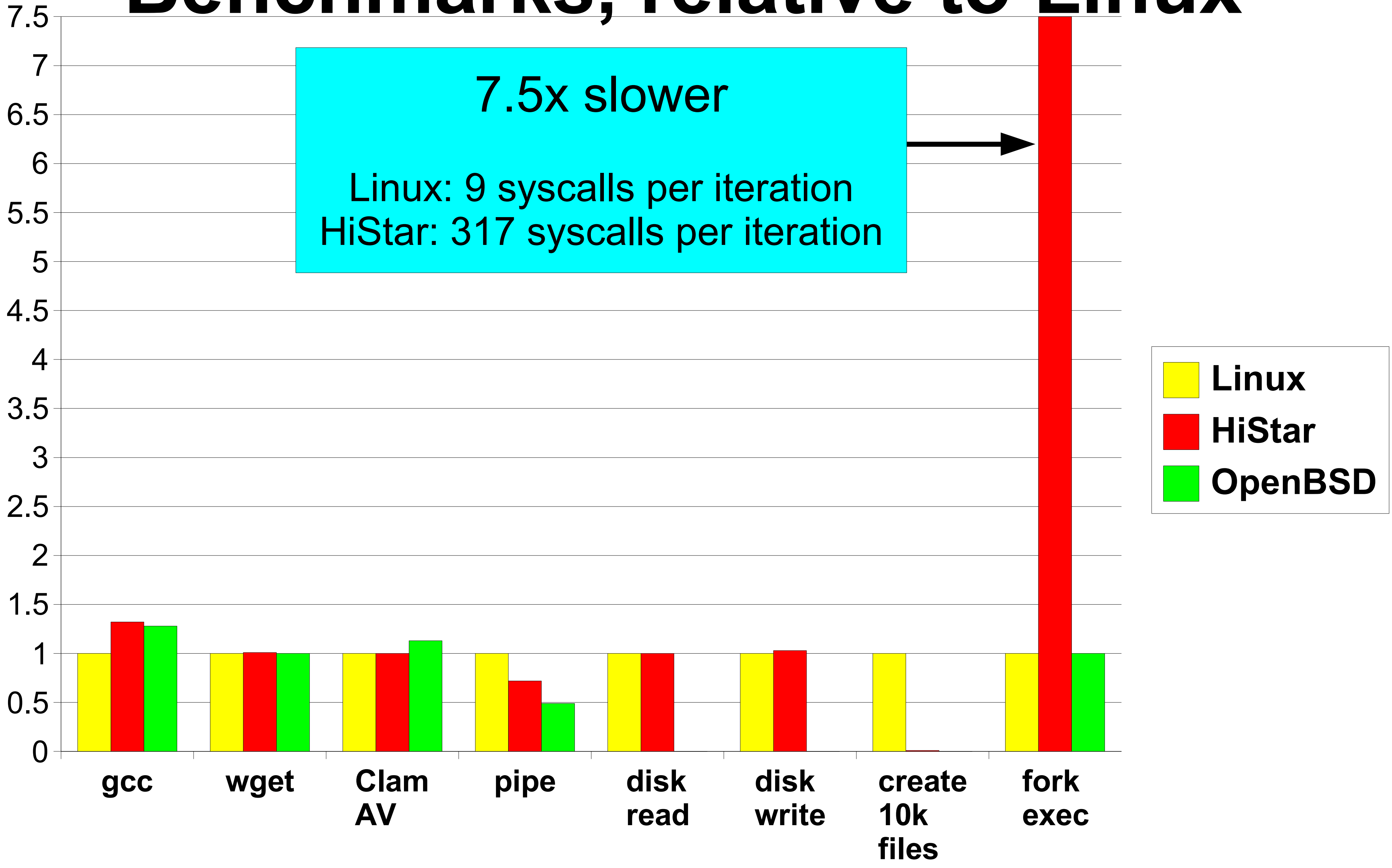


217x faster!

Synchronous creation of 10,000 files

HiStar allows use of group sync.
Application either runs to completion, or appears to never start (single-level store)

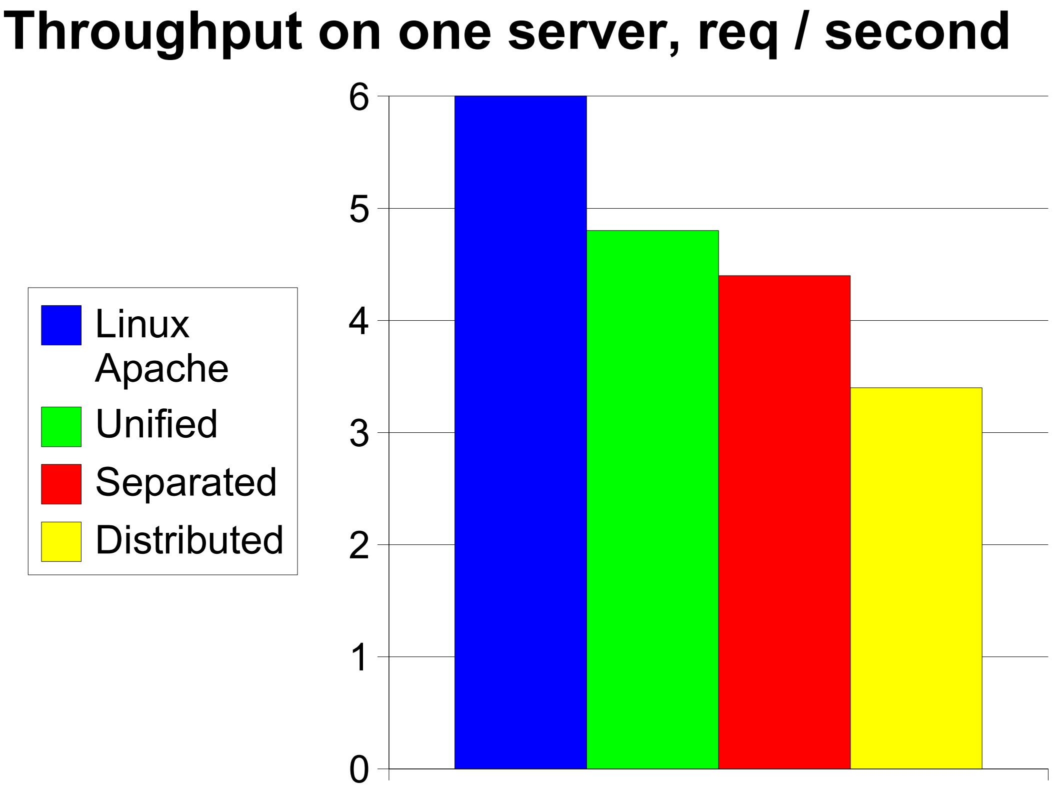
Benchmarks, relative to Linux



7.5x slower

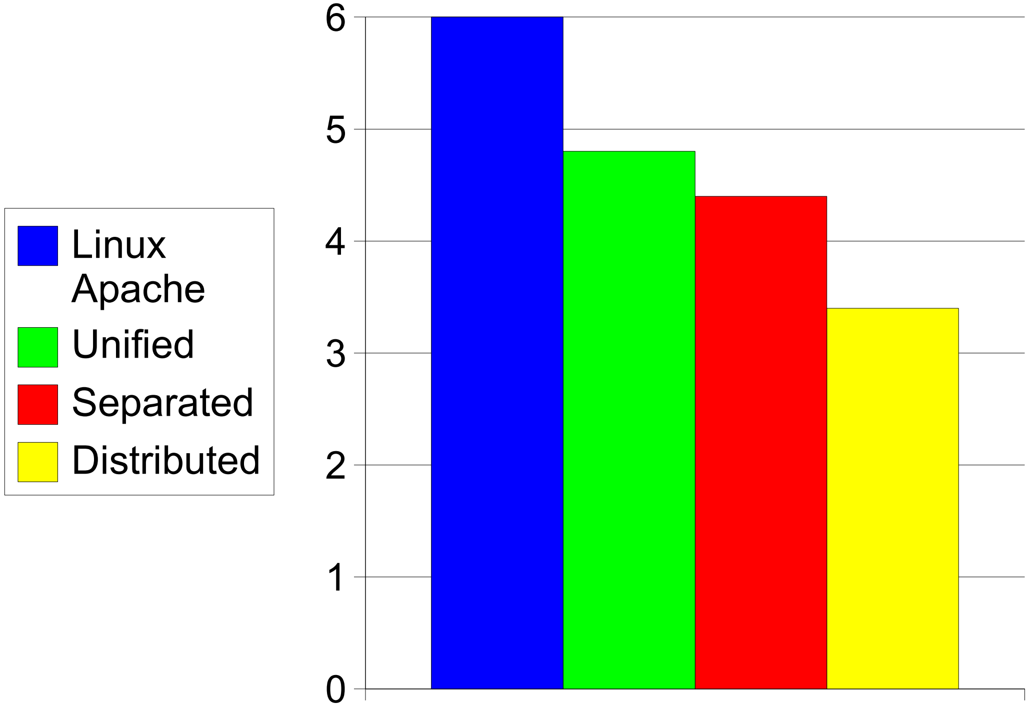
Linux: 9 syscalls per iteration
HiStar: 317 syscalls per iteration

Web server: “PDF maker” app

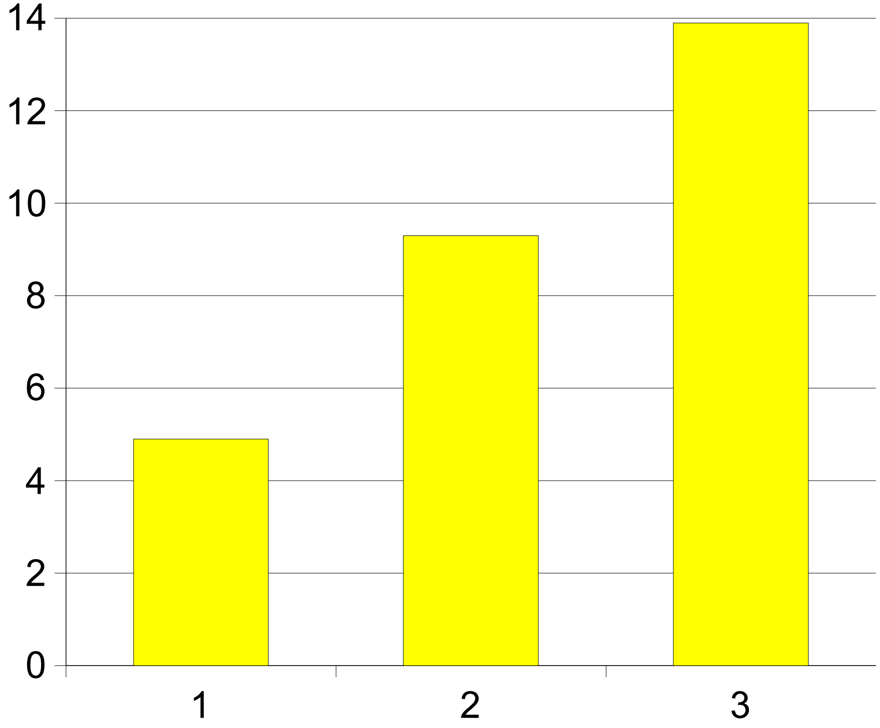


Web server: “PDF maker” app

Throughput on one server, req / second



Scalability of application servers (Fixed number of other servers)



Related Work

- *Asbestos* inspired this work
- Capability-based systems: *KeyKOS, EROS*
- Distributed capability systems: *Amoeba*
- Language-based security: *Jif, Joe-E*

Asbestos: Built for a web server

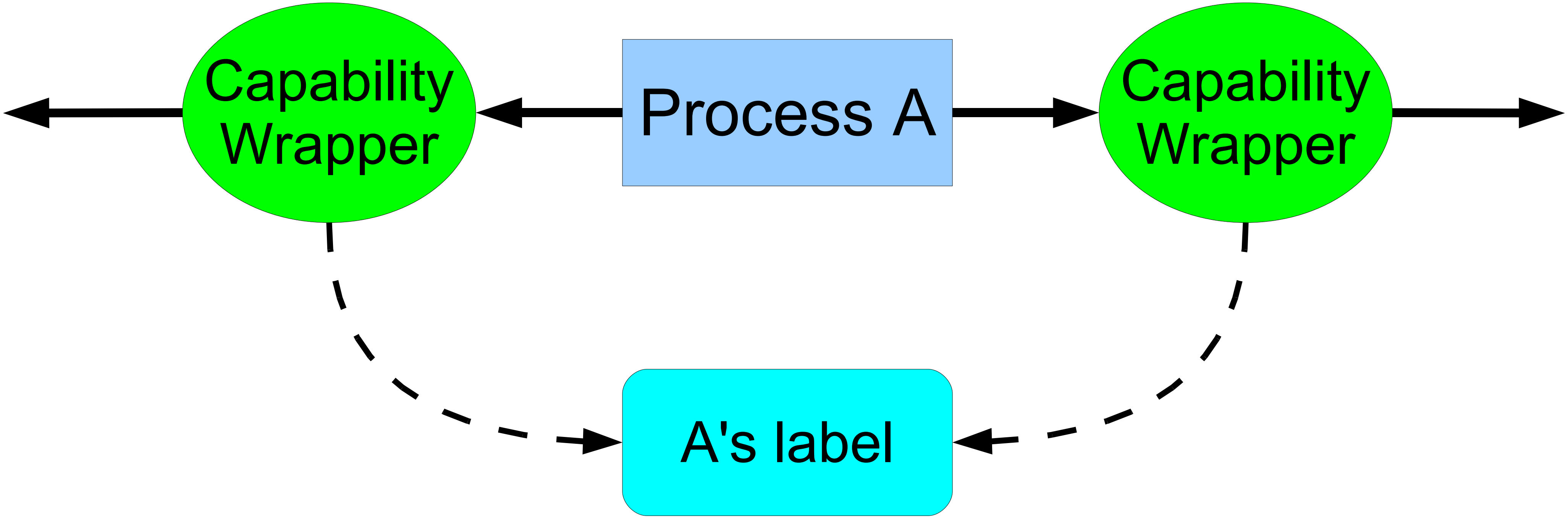
- HiStar closes covert channels inherent in the Asbestos design (mutable labels, IPC, ...)
- Lower-level kernel interface
  - Process vs Container+Thread+AS+Segments+Gates
  - 2 times less kernel code than Asbestos
  - Generality shown by the user-space Unix library
- System-wide support for persistent storage
  - Asbestos uses trusted user-space file server
- Resources are manageable
  - In Asbestos, reboot to kill runaway process

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



Distributed Capabilities (Amoeba)

- Servers require properly-signed capabilities

- Attacker cannot make up arbitrary capabilities
  - Must authenticate to access user's file server

- Attacker ***can*** create capabilities for his server
  - Cannot prevent code from “calling home”

Language-based security

- Much more fine-grained control
- Resource allocation covert channels hard to fix
- Many 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 halting to remove taint on thread