Machine-Independent Virtual Memory Management for Paged Uniprocessor and Multiprocessor Architectures

And

Labels and Event Processes in the Asbestos Operating System

Presented by Petko Nikolov

9/22/09

Mach

- Problem
  - OS portability suffers due to diff. memory structures
- Solution
  - Portable, multiprocessor OS – Mach
  - Few assumptions about memory hardware
    - Just recover from page faults

Mach VM

- Supports:
  - Large, sparse virtual address spaces
  - Copy-on-write virtual copy operations
  - Copy-on-write and read-write memory sharing
  - Memory mapped files
  - User-provided backing store objects and pagers

Mach Design

- Task
- Thread
- Port
- Message
- Memory object

VM Operations

- A task can:
  - Allocate a region of VM on a page boundary
  - Deallocate a region of VM
  - Set the protection status of a region
  - Specify the inhertance of a region
  - Create and manage a memory object

Implementation

- 4 basic memory management data structures:
  - Resident page table
  - Address map
  - Memory object
  - Pmap
- Machine dependent vs independent

Resident Memory

- Physical memory – cache for virtual memory objects
- Physical page entries linked into:
  - Memory object list
  - Memory allocation queues
  - object/offset hash bucket

Address Maps

- Doubly-linked list of address map entries
- Map range of virtual addresses to area in virtual object
  - Contiguous
- Efficient for most frequent operations:
  - Page fault lookups
  - Copy/protection operations on address ranges
  - Allocation/deallocation of address ranges

Memory Objects

- Repository for data, indexed by byte
  - Resembles a UNIX file
- Reference counters allow garbage collection
- Pager – memory object managing task
  - Handles page faults, page-out requests outside of kernel

Sharing Memory

- Copy-on-write
  - Shadow objects
  - Remembers modified pages
- Read/write sharing
  - Memory object not appropriate for this
  - Must use sharing maps

Object Tree

- Must prevent large chains of shadow objects
  - Utilize GC for shadow objects
- Unnecessary chains occurs during heavy paging
  - Cannot be detected easily
- Complex locking rules

pmap

- Management of physical address maps
  - Only machine-dependent module
  - Implement page-level operations
  - Ensure hardware map is operational
  - Need not keep track of all currently valid mappings
- Machine-independent parts are the driving force of Mach VM operations

Porting Mach VM

- Code for VM originally ran on VAX machines
- IBM RT PC
  - Approx. 3 weeks for pmap module
- Sequent Balance
  - 5 weeks – bootable system
- Sun 3, Encore MultiMAX

Performance

Performance of Mach VM Operations

Operation		Mach	UNIX
zero fill 1K (RT PC)		.45ms	.58ms
zero fill 1K(uVAX II)		.58ms	1.2ms
zero fill 1K(SUN 3/160)	.23ms	.27ms	
fork 256K (RT PC)		41ms	145ms
fork 256K (uVAX II)		59ms	220ms
fork 256K (SUN 3/160)	68ms	89ms	
read 2.5M file(VAX 8200)	(system/elapsed sec)		
first time		5.2/11sec	5.0/11sec
second time		1.2/1.4sec	5.0/11sec
read 50K file (VAX 8200)	(system/elapsed sec)		
first time		.2/.3sec	.2/.5sec
second time		.1/.1sec	.2/.2sec

Table 7-1:

The cost of various measures of virtual memory performance for Mach, ACIS 4.2a, SunOS 3.2, and 4.3bsd UNIX.

Summary

- Sophisticated, hardware-independent VM system possible
- Can achieve good performance in some cases

Asbestos

Labels and Event Processing in the Asbestos Operating System

With slides borrowed from SOSP 2005 Asbestos presentation

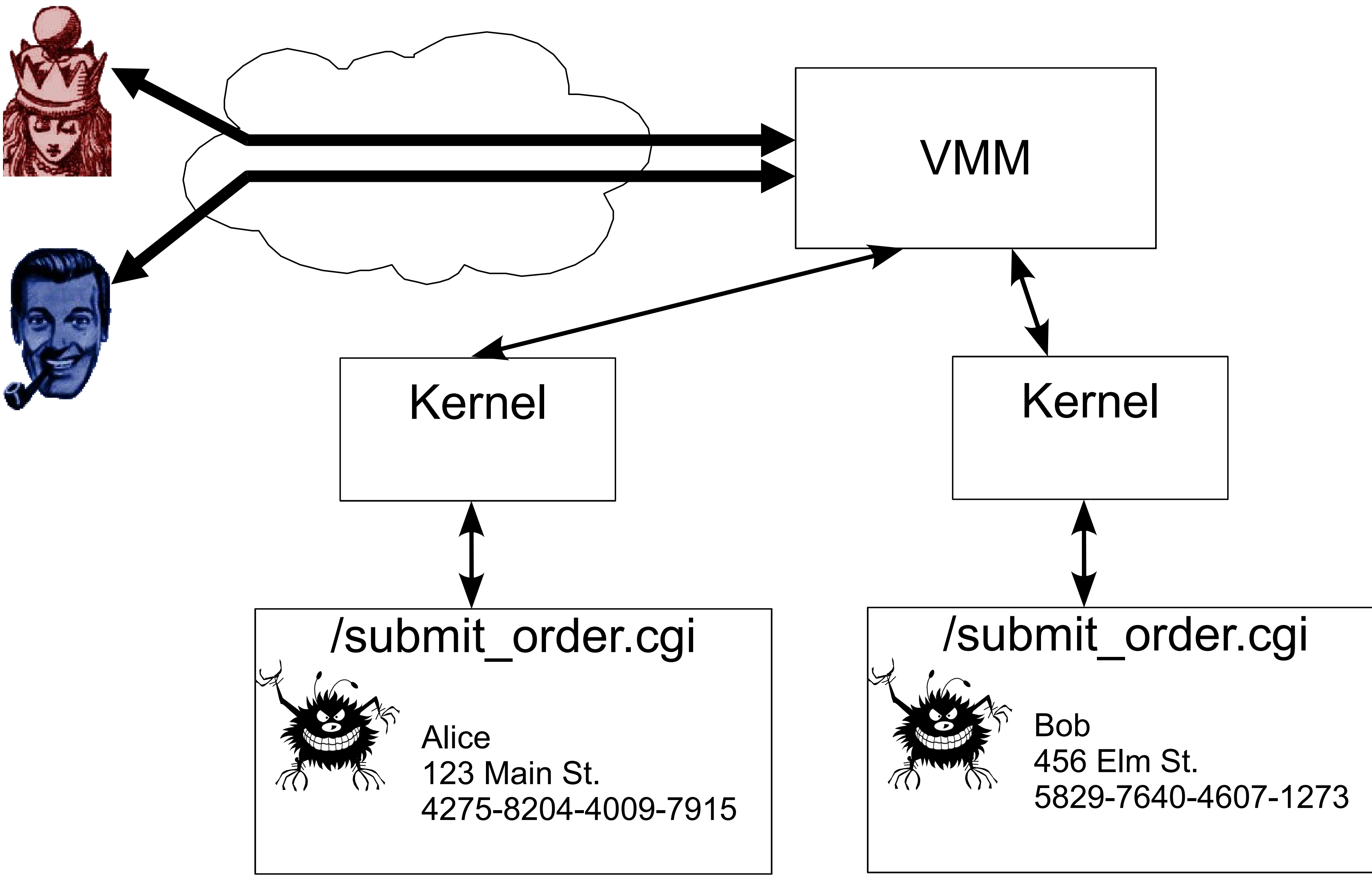
Asbestos Outline

- Why is it needed?
- Other models
  - Virtual machines
- Asbestos OS
  - Labels
  - Event processes
- Asbestos OKWS
- Performance

The Problem

- Web servers have exploitable software flaws
  - SQL injection, buffer overrun
- Private information leaked
  - Credit card #'s, SS #'s
  - All data potentially exposed due to single flaw
- Lack of isolation of user data
- Unconstrained information flow

Virtual Machine Isolation



Problem with VM Isolation

- Course-grained sharing/isolation
- Heavy on resources
- Clumsy way to handle problem
  - Requires separate instance of OS for each label
  - Should really have support for this in OS

Information Flow Control Systems

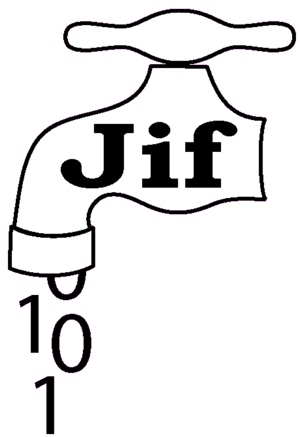
- Conventional multi-level security
  - Kernel-enforced information flow control across processes
  - A handful of *levels* and *compartments*: “secret, nuclear”
  - Inflexible, administrator-established policies
  - Central authority, no privilege delegation
- Language-enforced information flow (Jif)
  - Applications can define flexible policies at compile time
  - Enforced within one process
- **Asbestos**
  - Applications can define flexible policies
  - Kernel-enforced across all processes

Approaches

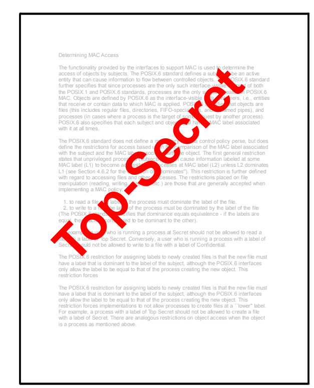
Policy defined by:

Application

Kernel



Asbestos



Conventional MLS

Within a process

Across processes

Asbestos Goal

Asbestos should support efficient, unprivileged, and large-scale server applications whose application-defined users are isolated from one another by the operating system, according to application policy.

Asbestos Goal

- Large-scale
  - Changing population of thousands
- Efficient
  - Cache user data, while keeping it isolated
- Unpriviliged
  - Minimum privilege required
- Application defines notion of user
- Isolation of users' data
- Application policy
  - Application-defined, OS-enforced

Asbestos Overview

- IPC similar to that of Mach
  - Messages sent to ports
  - Asynchronous, unreliable
- Asbestos labels
  - Track, limit flow of information
- Event processes
  - Efficiently support/isolate many concurrent users

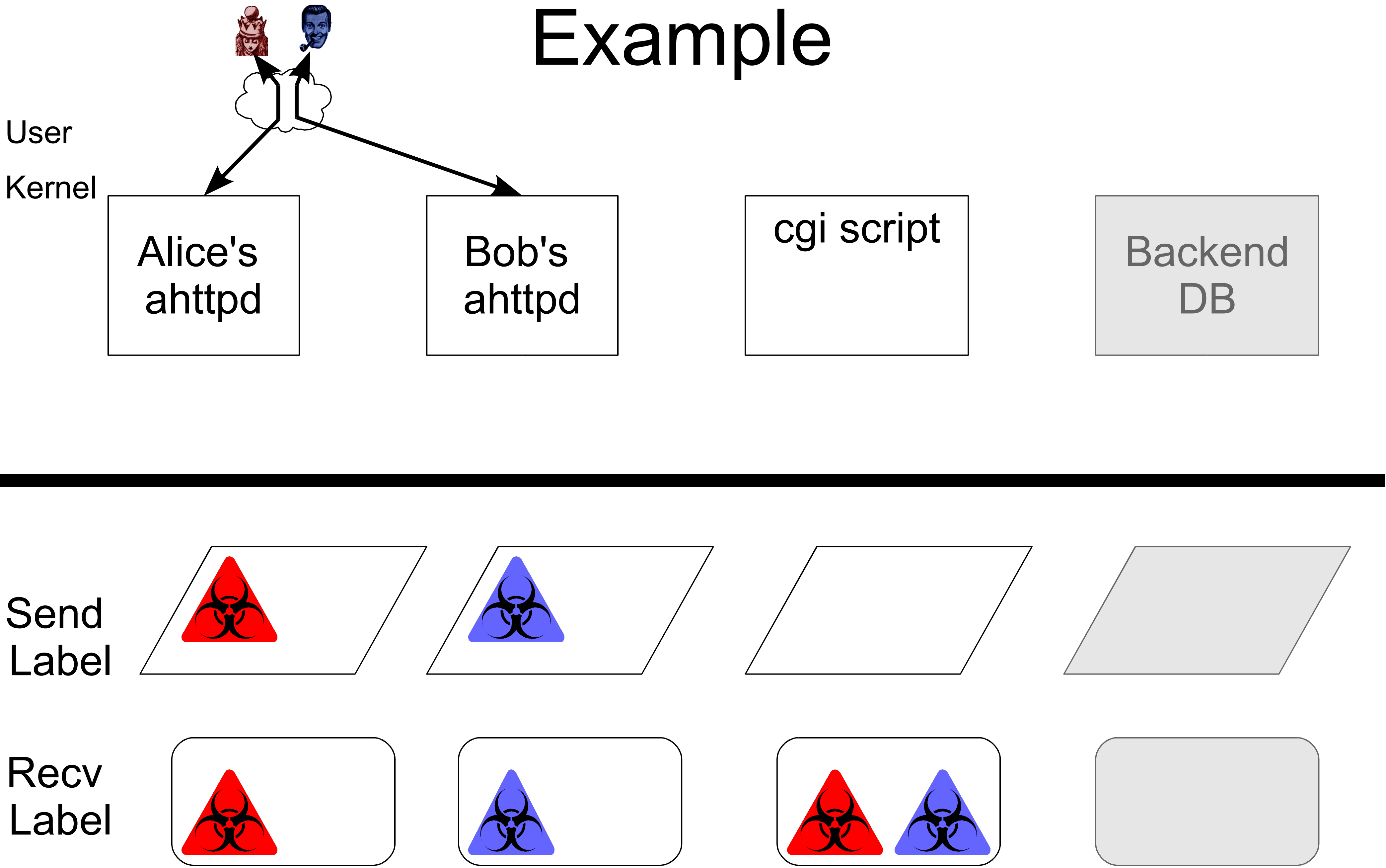
Compartments

- Contamination / label type
  - Mike's data, Michele's data, Peter's business data
- Created by application
  - Creator process can delegate rights

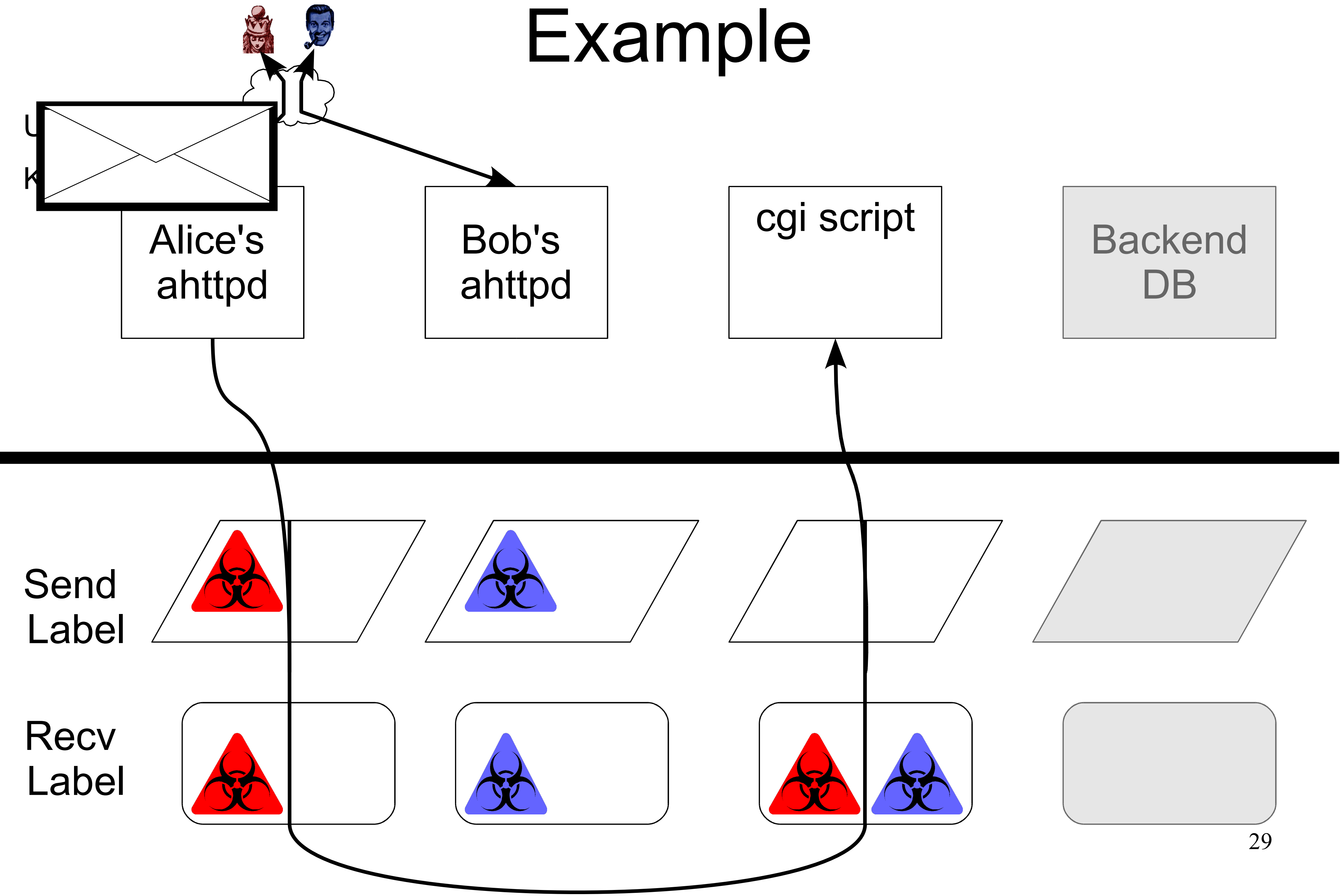
Labels

- Each process has send and receive label
  - Send label track current contamination
  - Receive label tracks max contamination (clearance)
- Rules enforced when messages are sent
- Contamination of receiver updated

Basic Example



Basic Example



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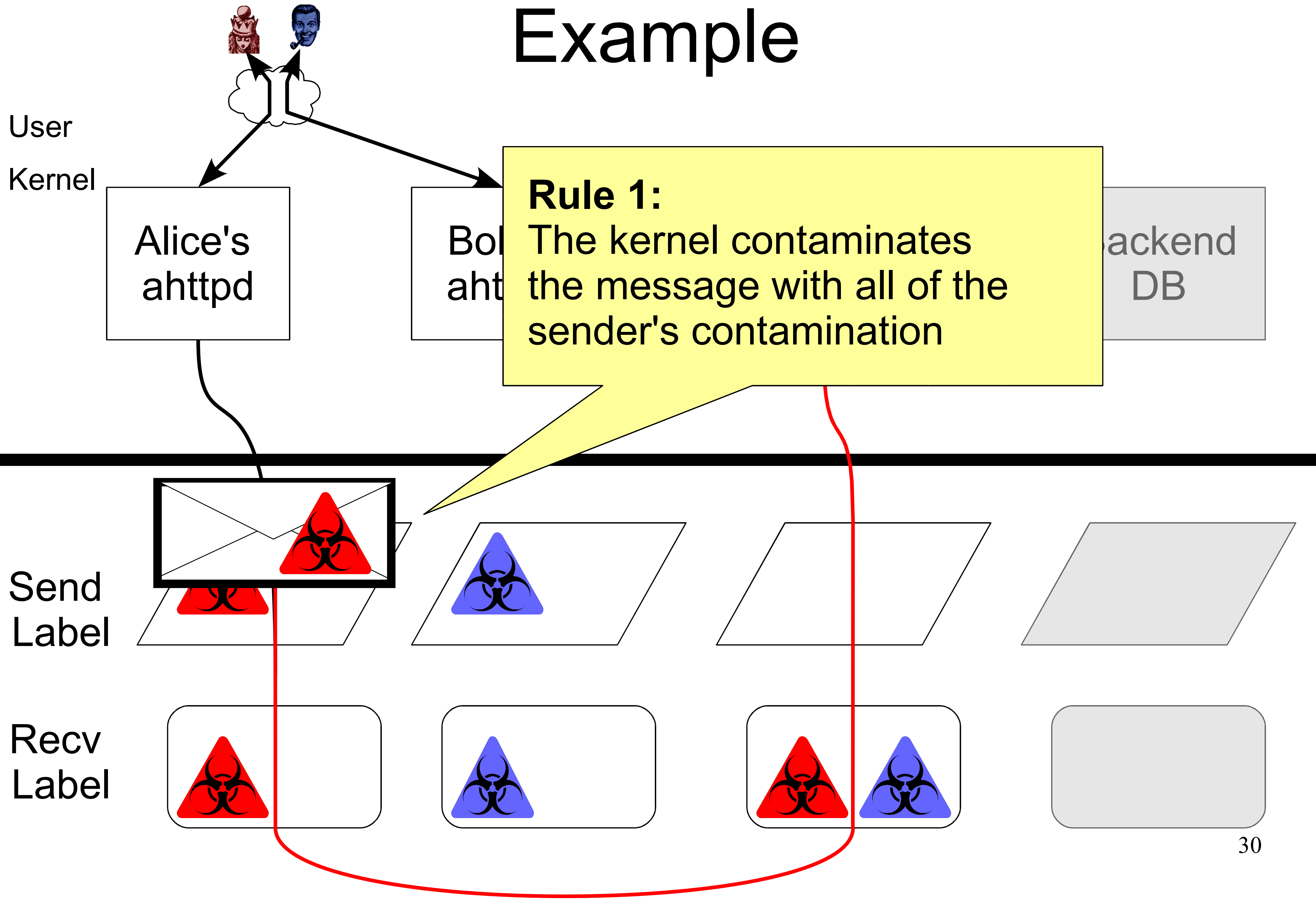

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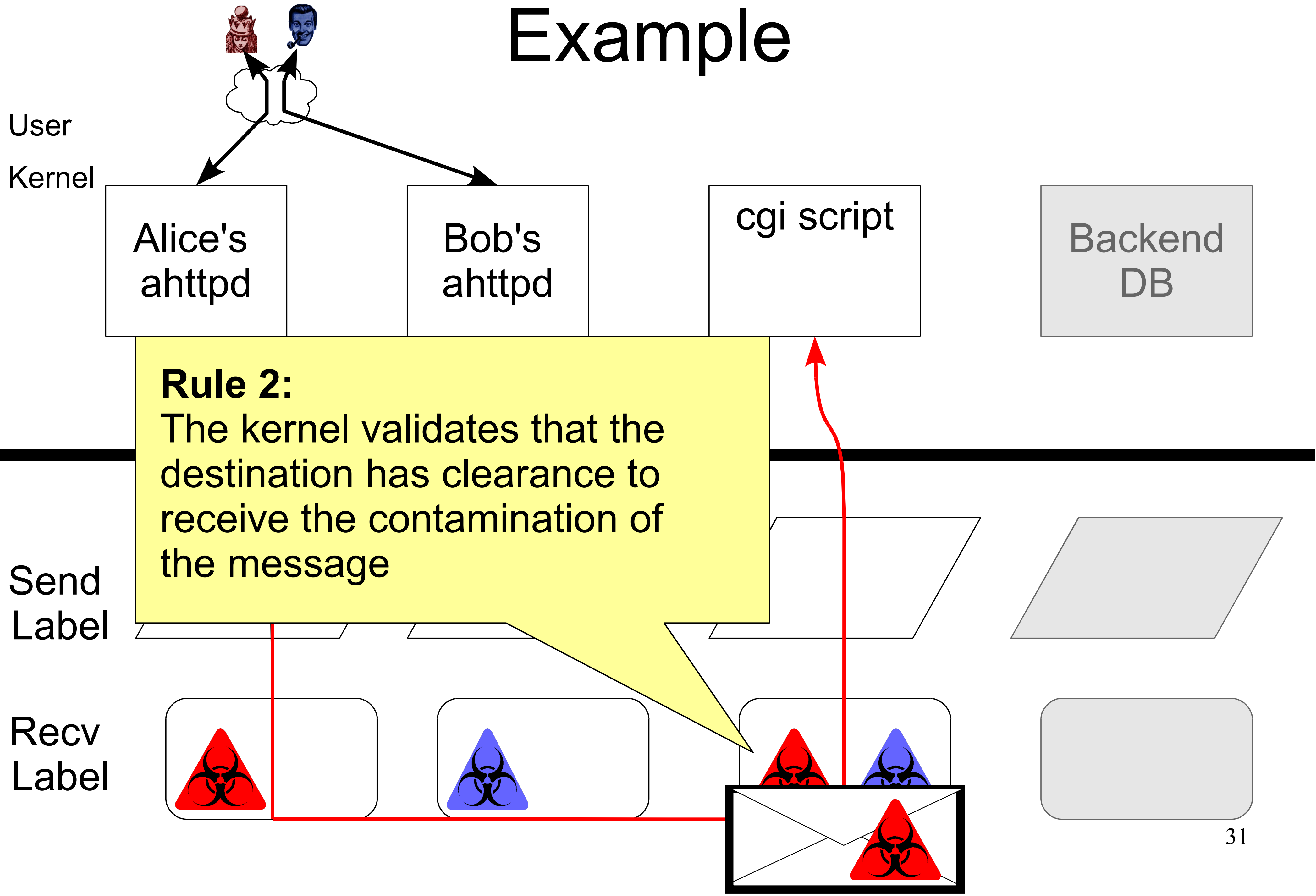
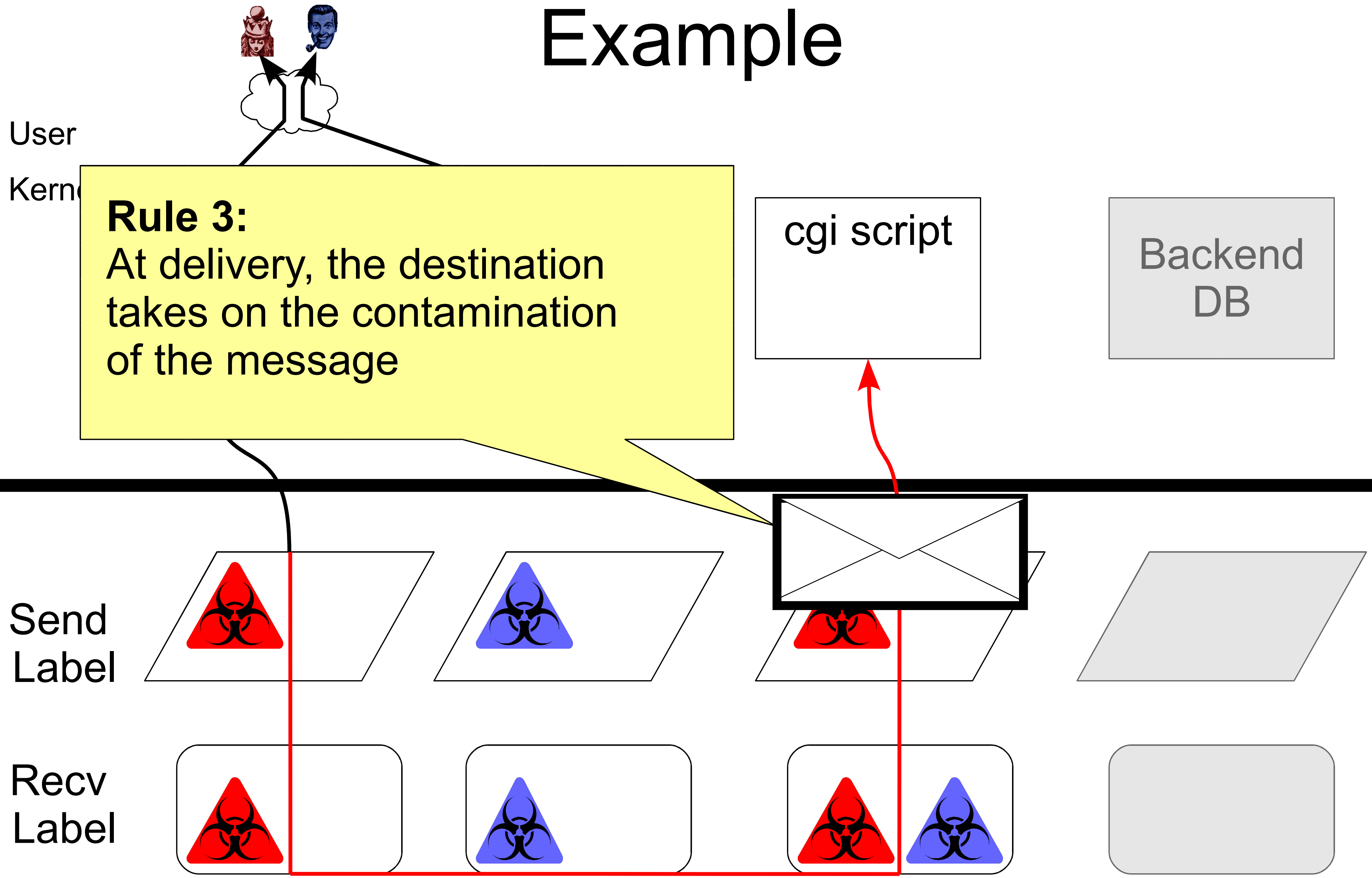


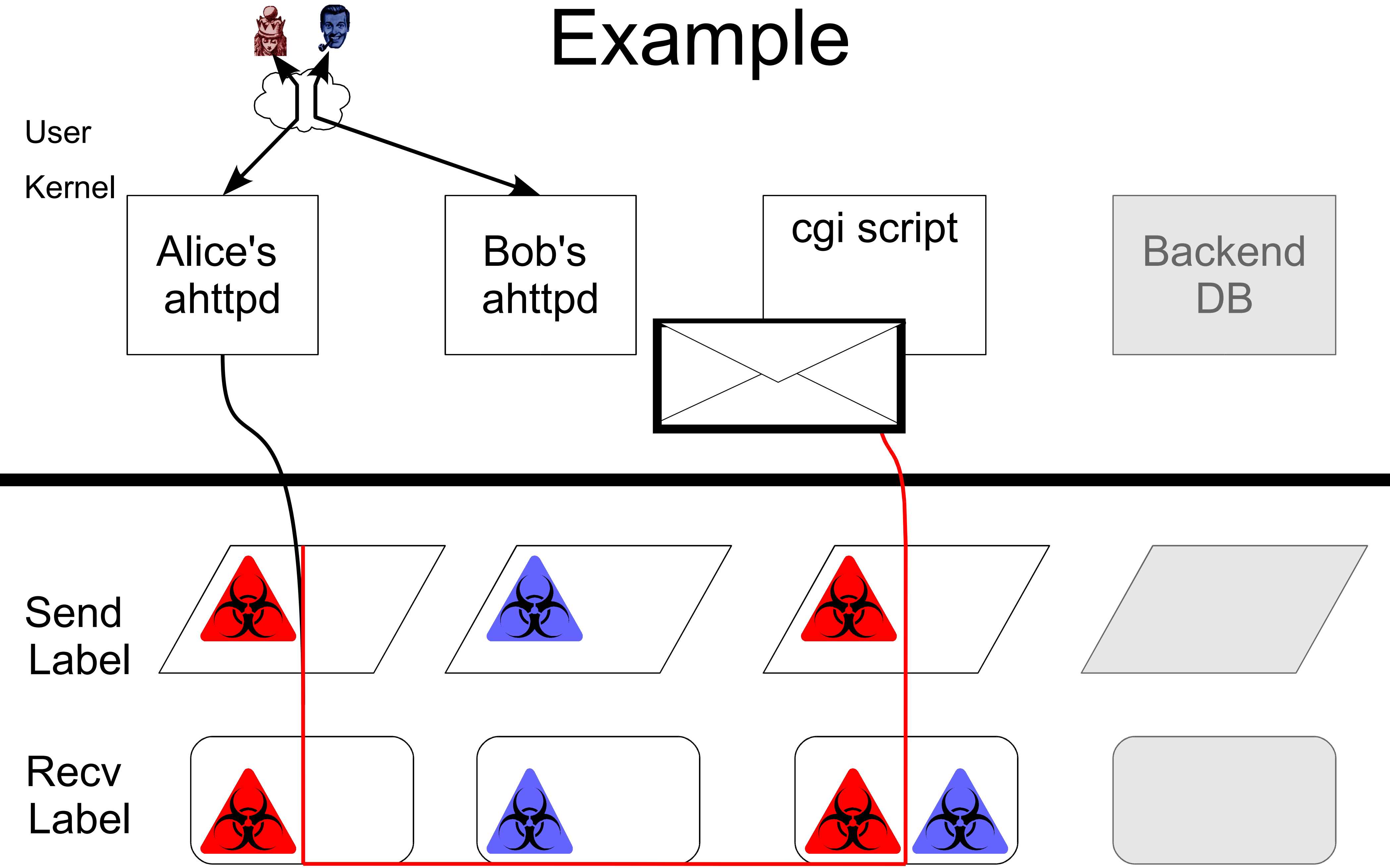
Rule 2:
The kernel validates that the destination has clearance to receive the contamination of the message

Basic Example

Rule 3:
At delivery, the destination takes on the contamination of the message

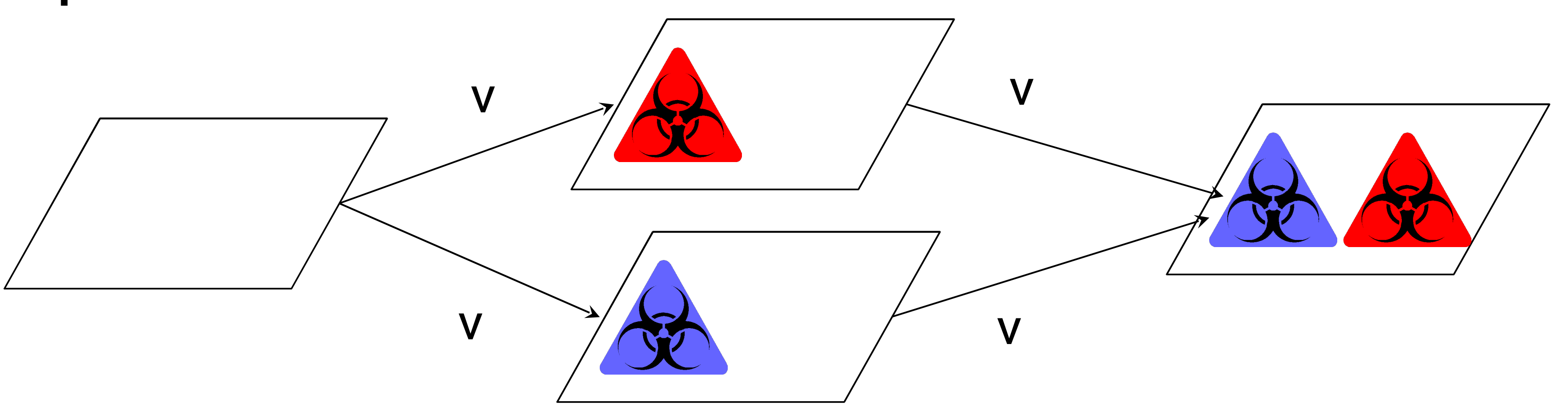


Basic Example

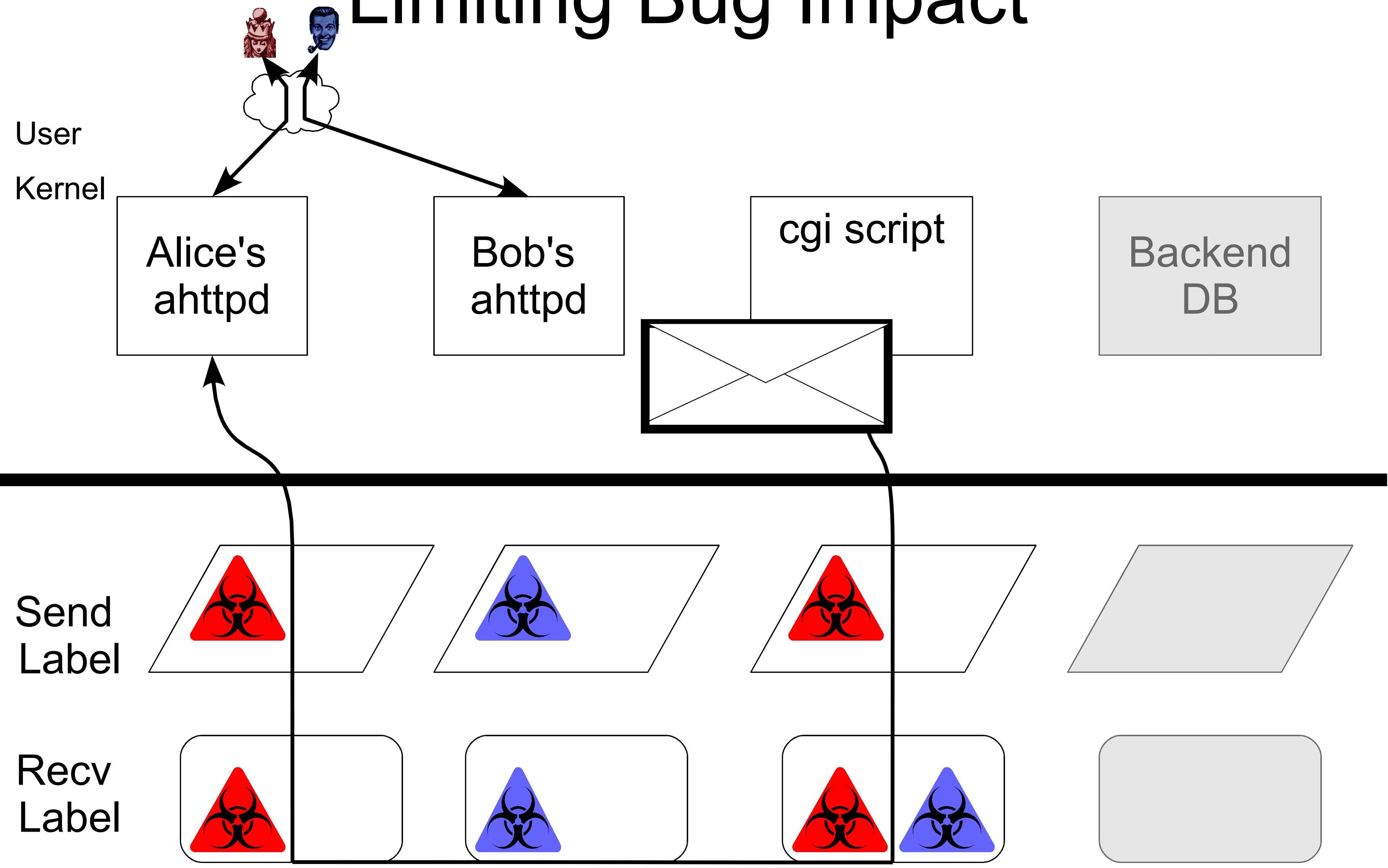


Implementing Clearance Checks

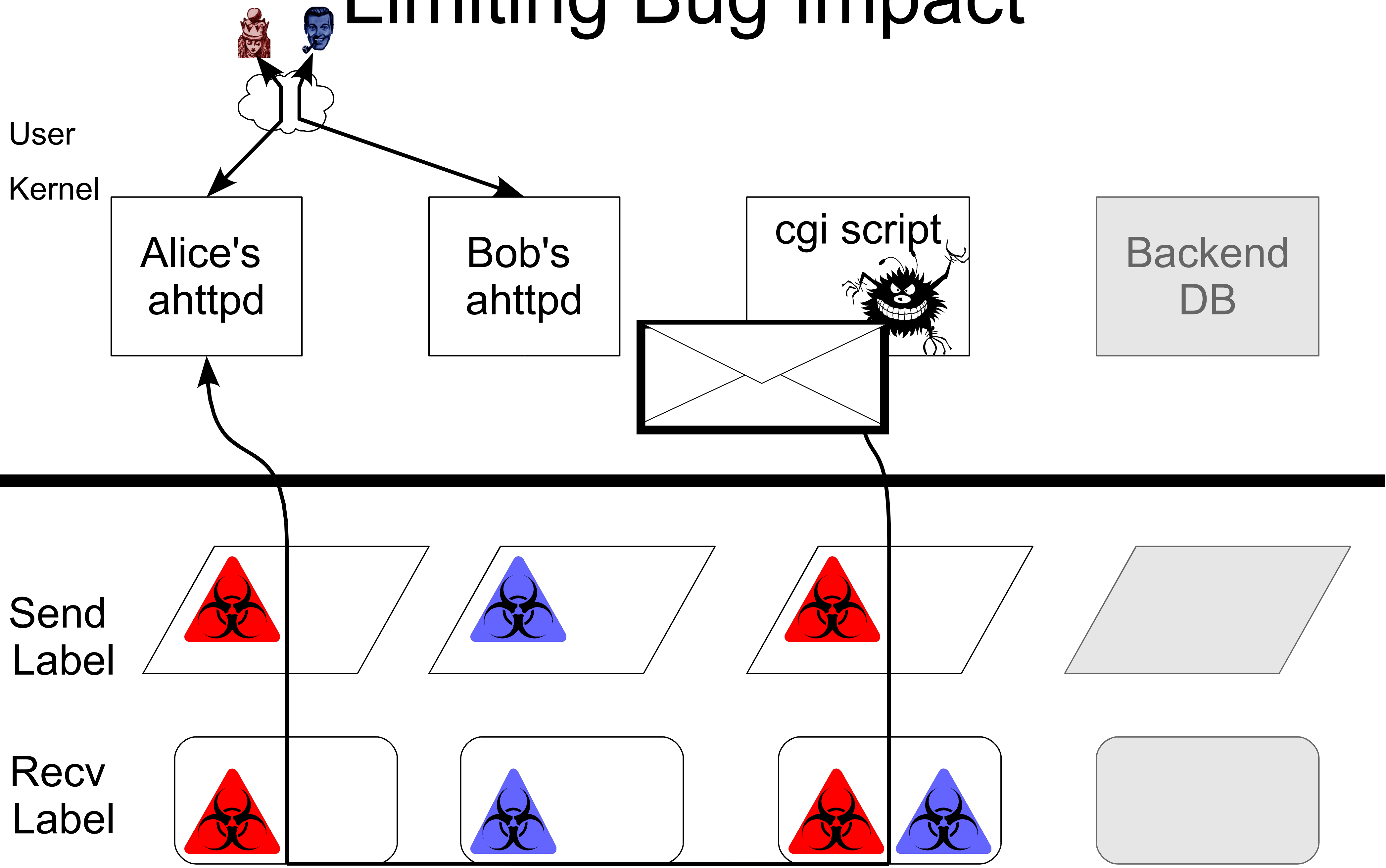
- How does the clearance check work?
- Labels form a lattice
- Partial ordering
  - Sender's send label must be less than or equal to the destination's receive label
- Send label updated with a least upper bound operator



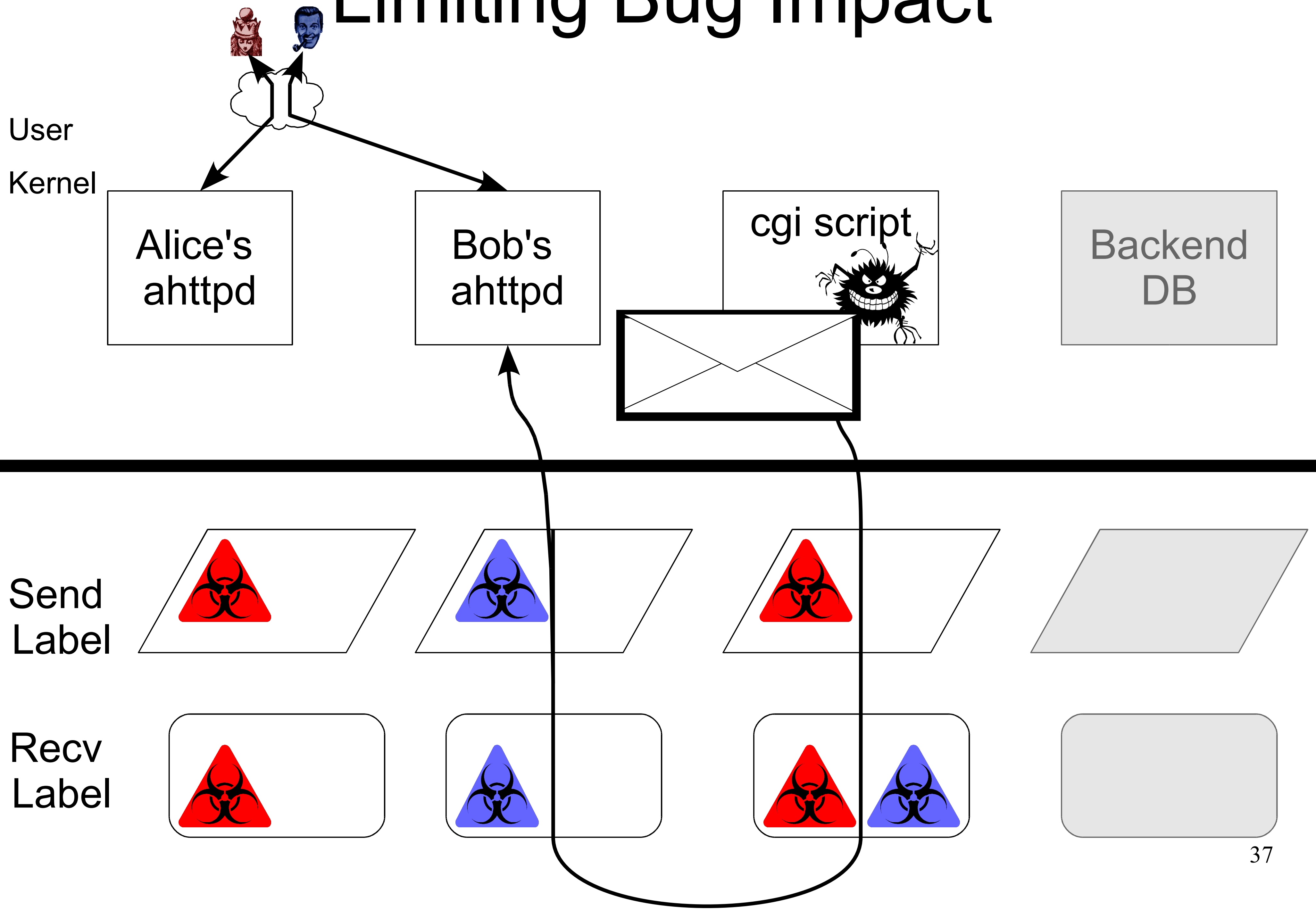
Limiting Bug Impact



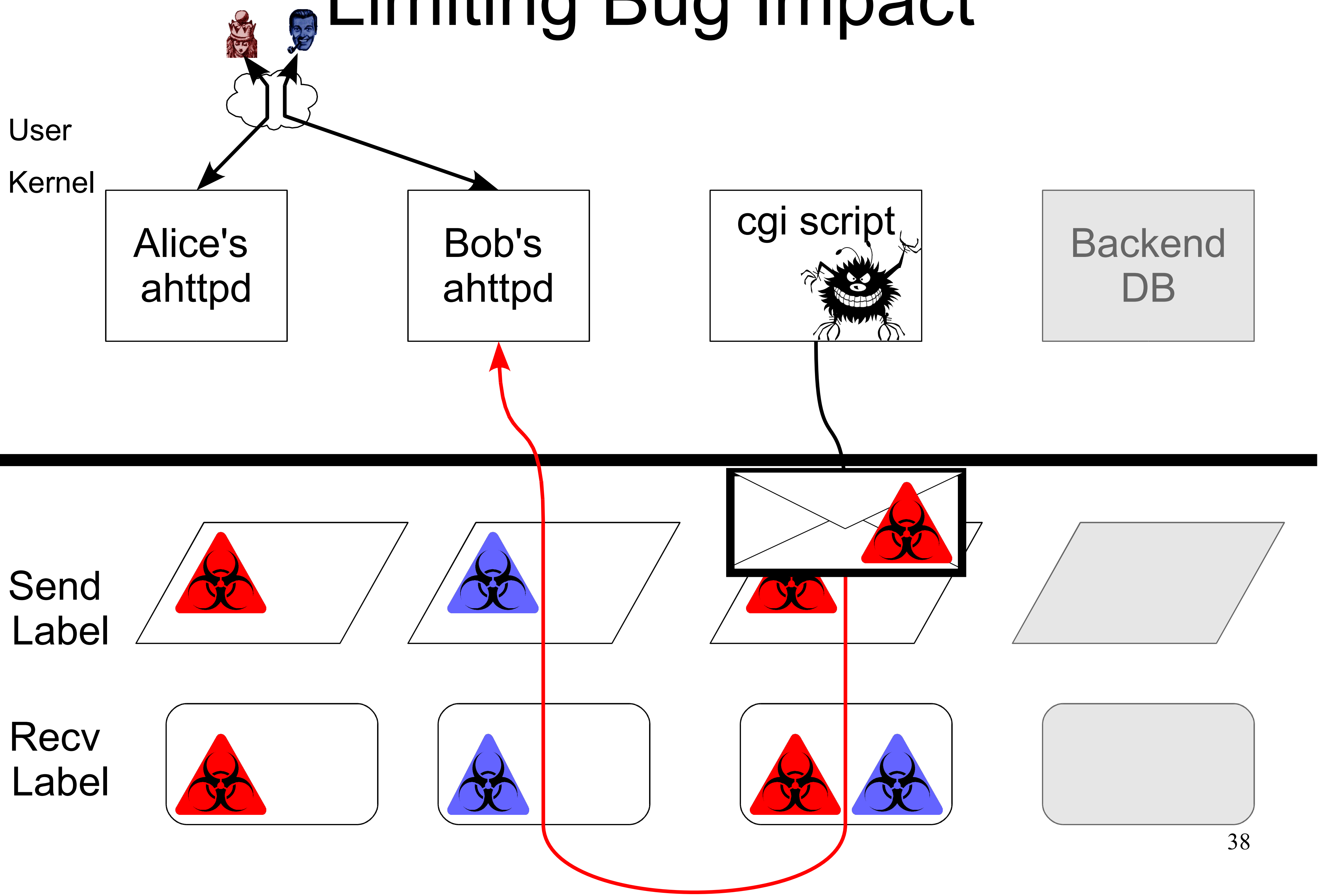
Limiting Bug Impact



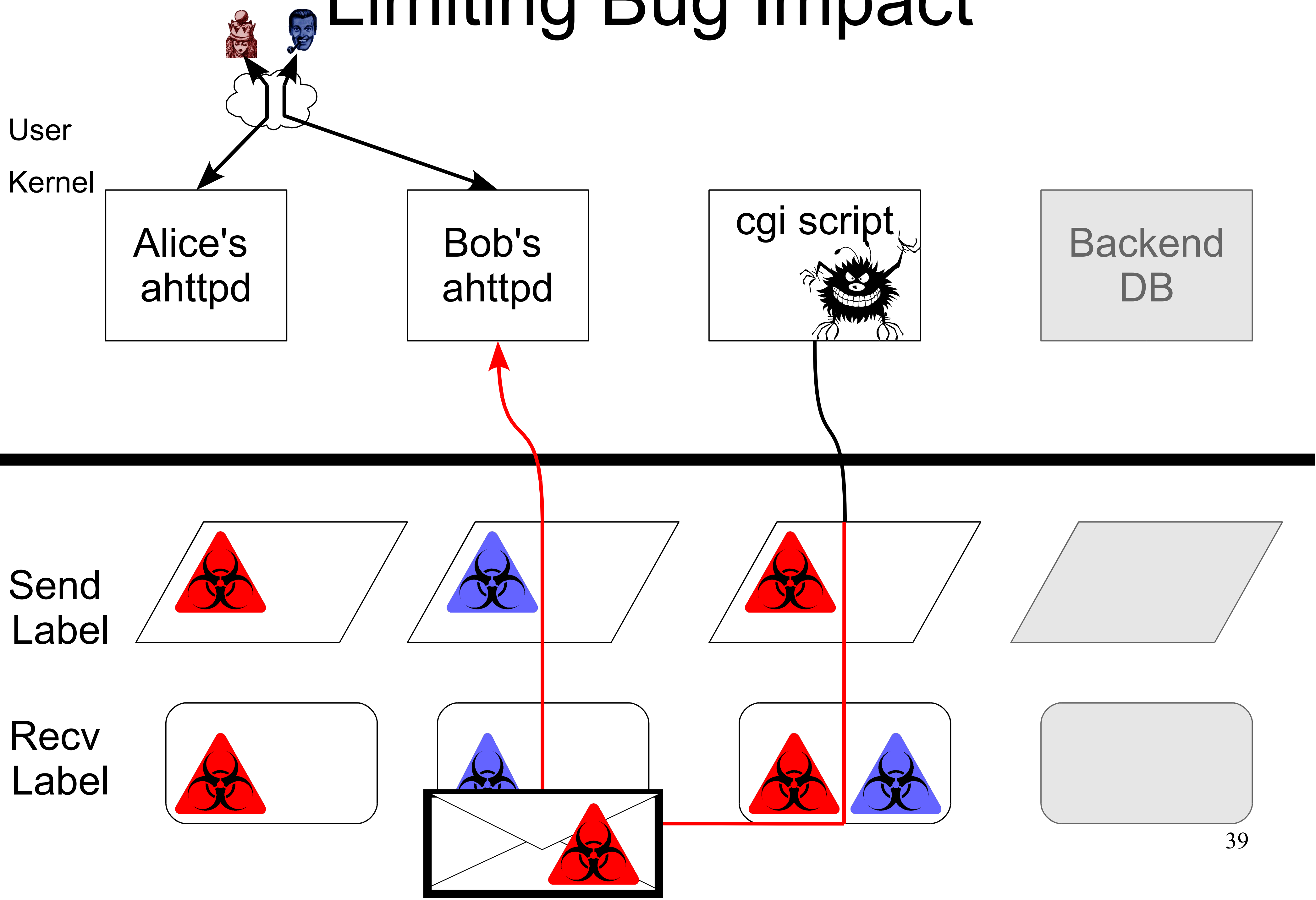
Limiting Bug Impact



Limiting Bug Impact



Limiting Bug Impact



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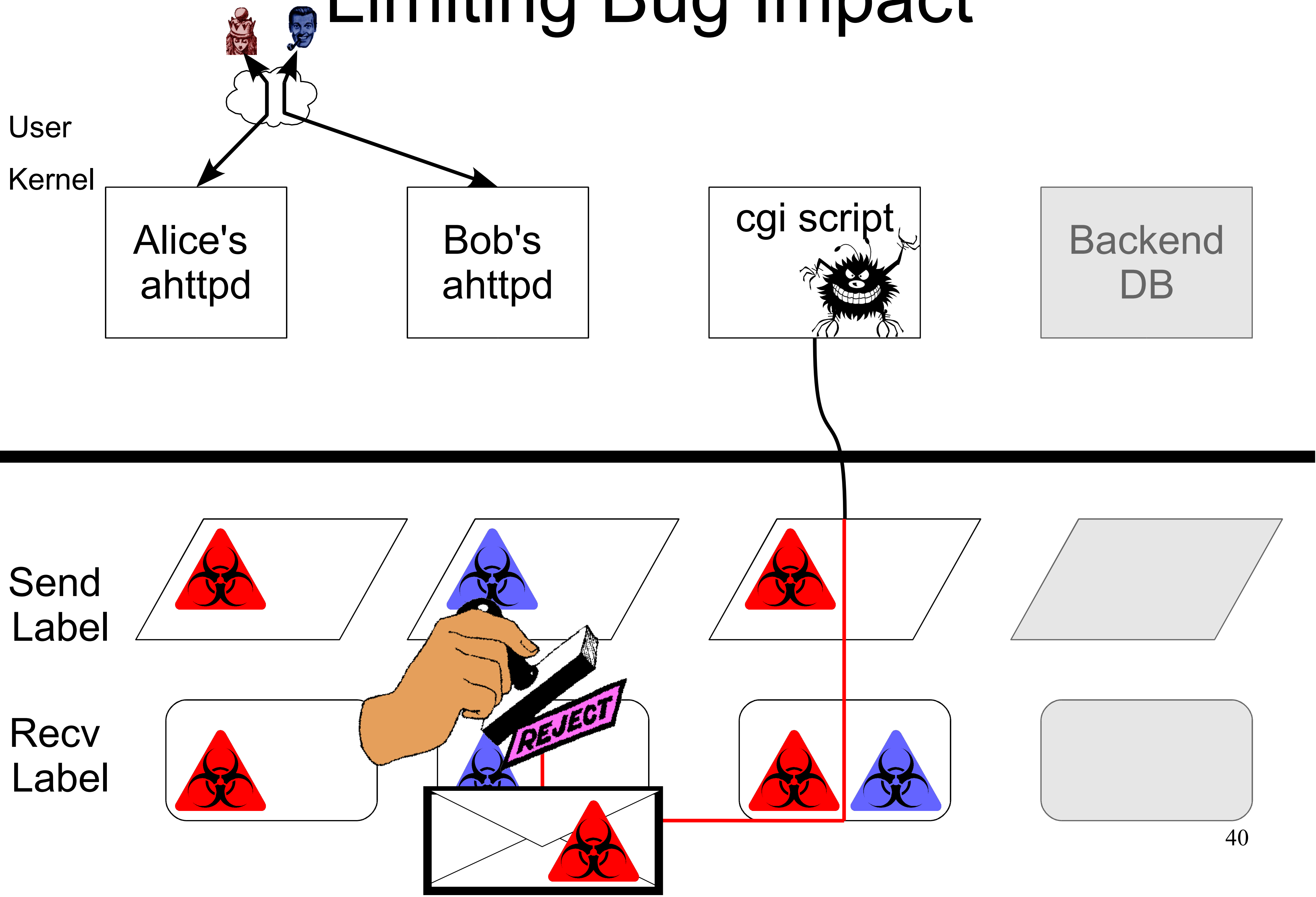
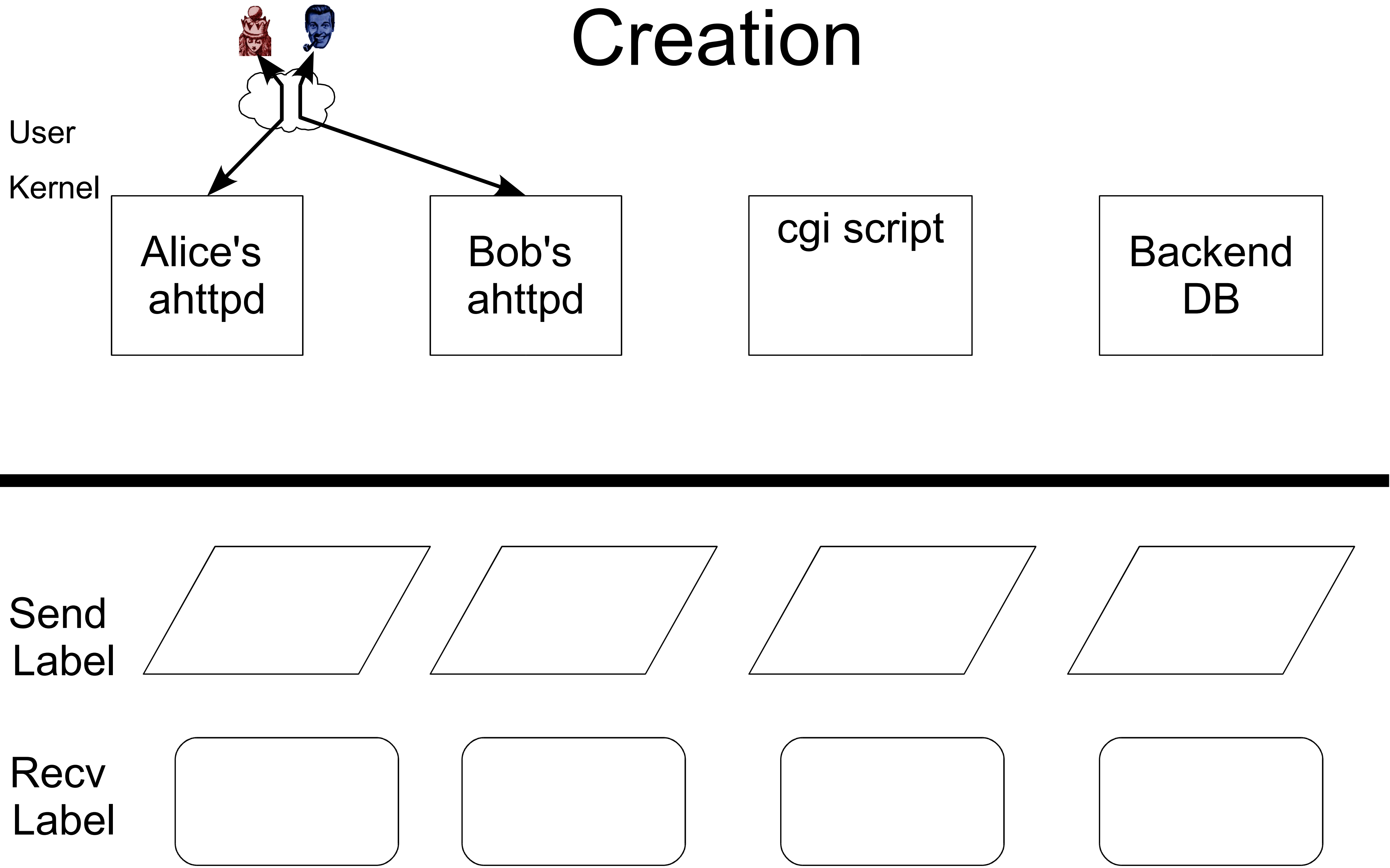


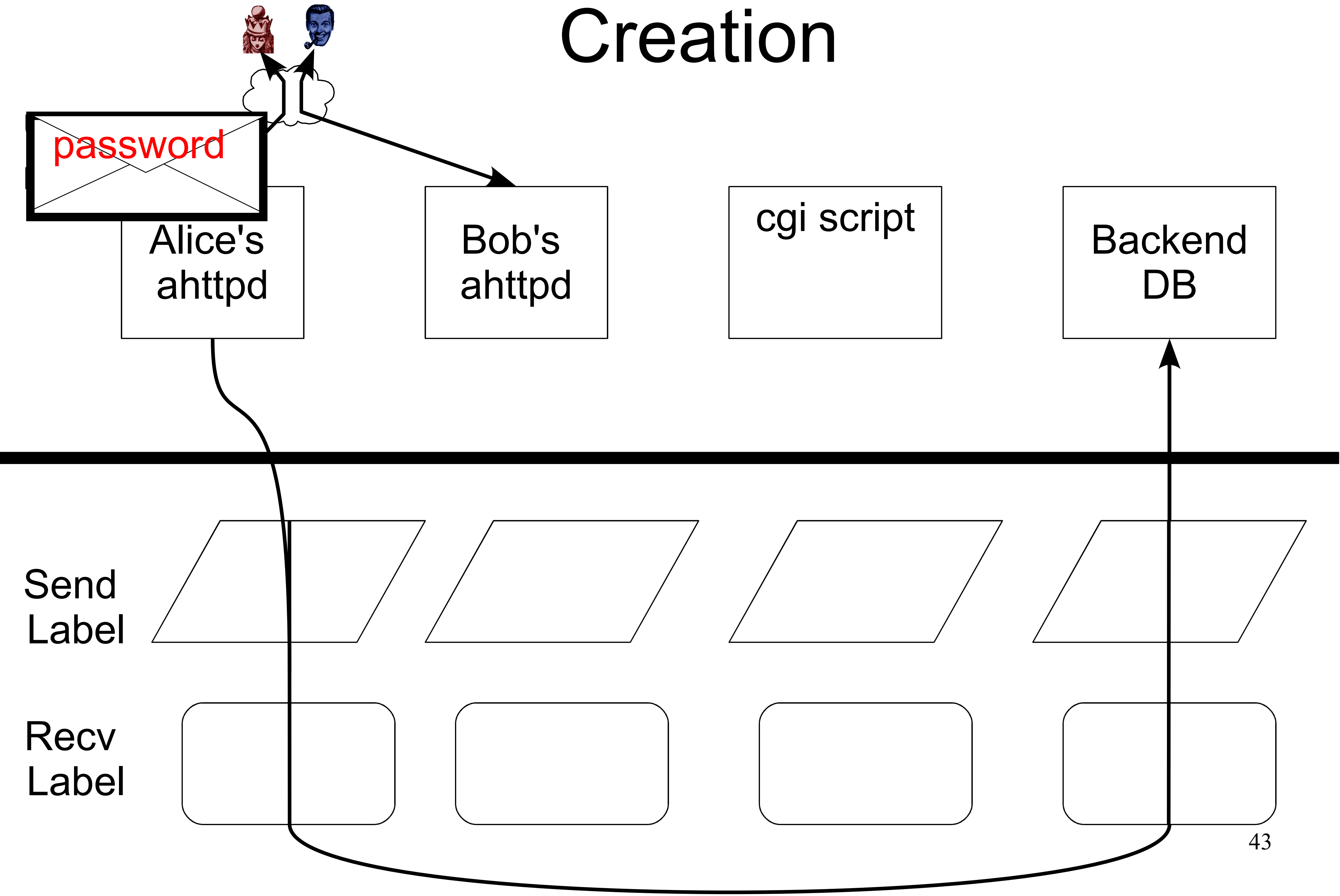
Application Defined Policies

- Where did the compartments come from?
- How did the labels get set the way they are?
- In traditional multi-level security systems, the system operator does these things
- Asbestos labels provide a decentralized and unprivileged method to set these initial conditions

Compartment Creation



Compartment Creation



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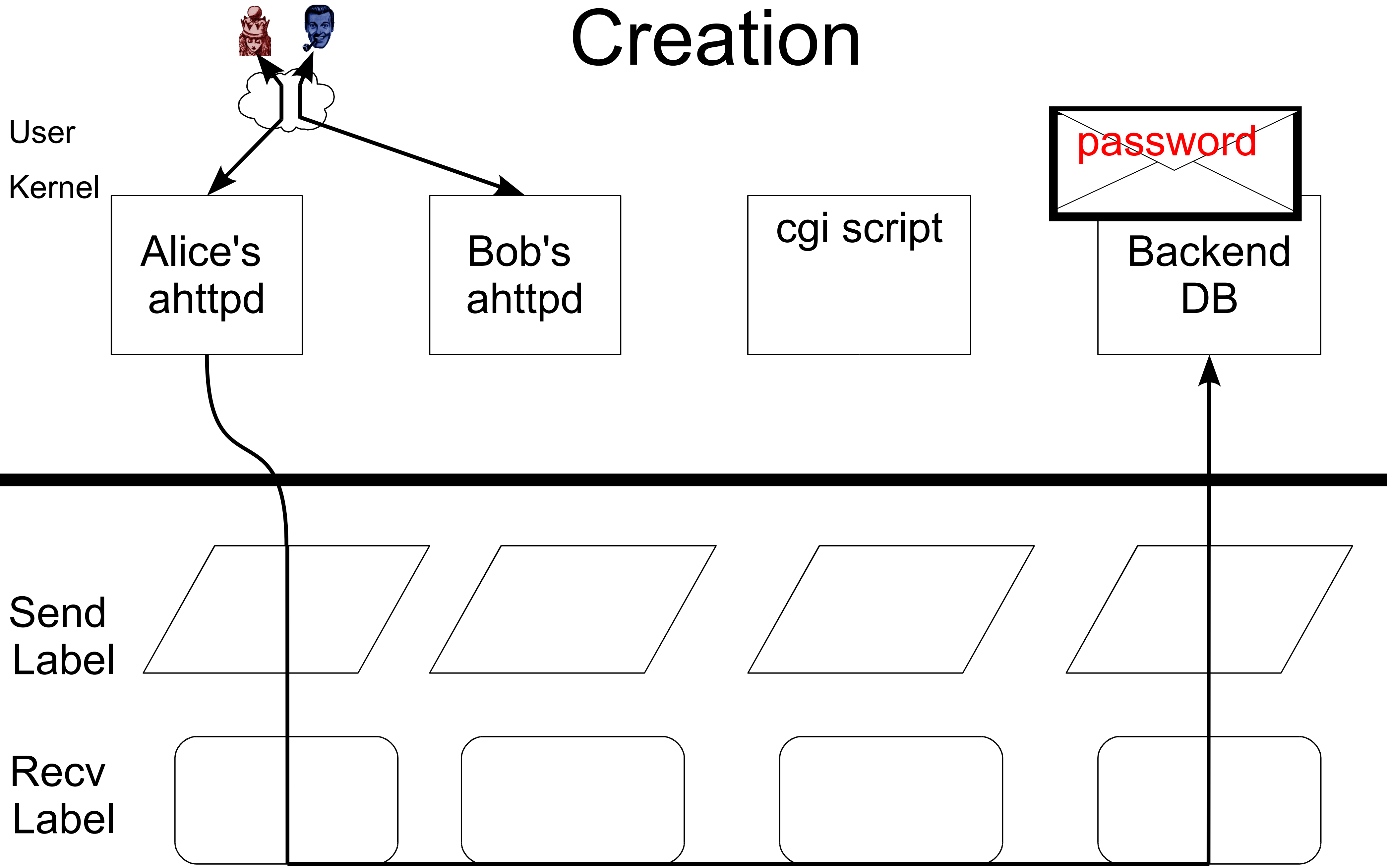

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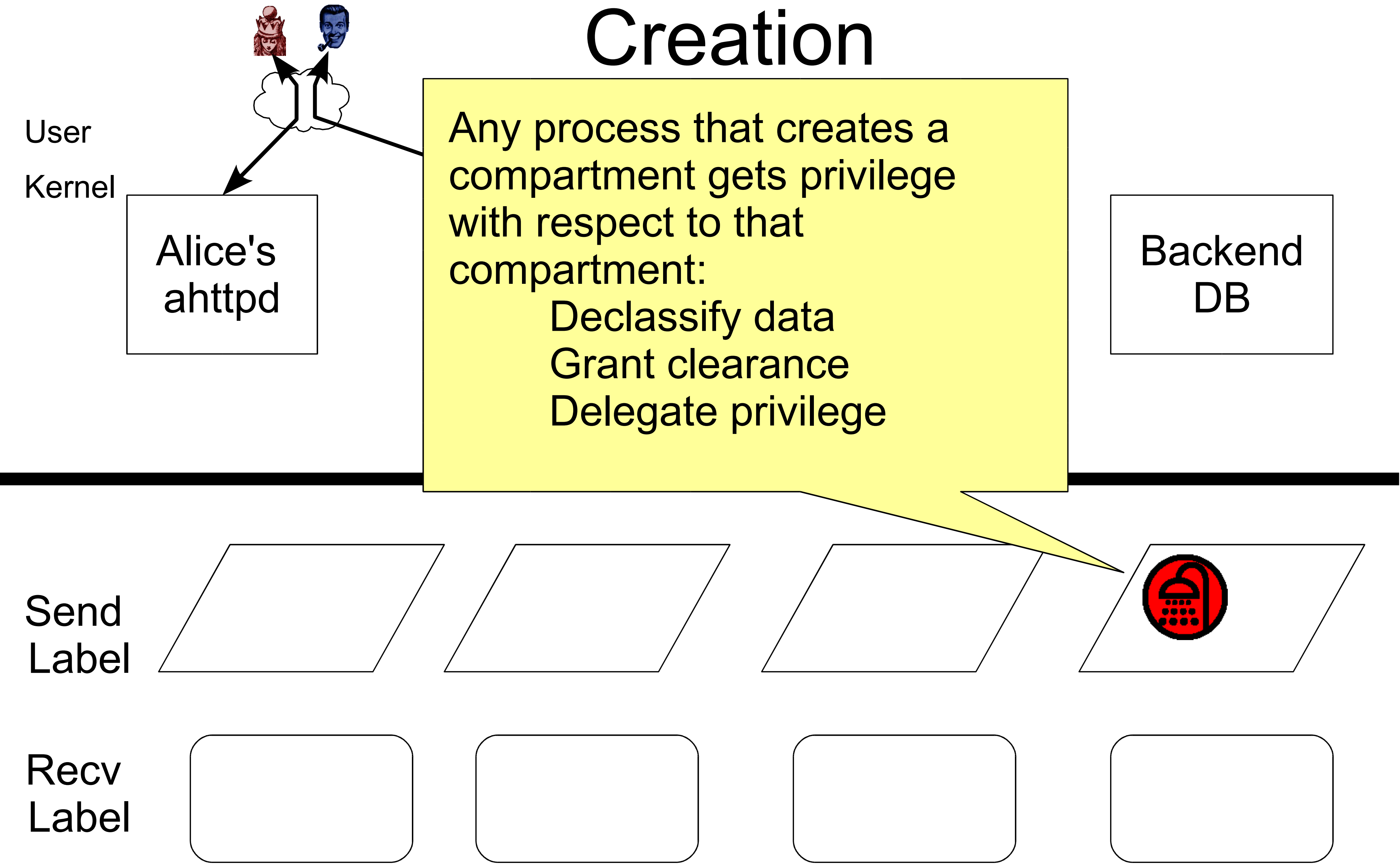
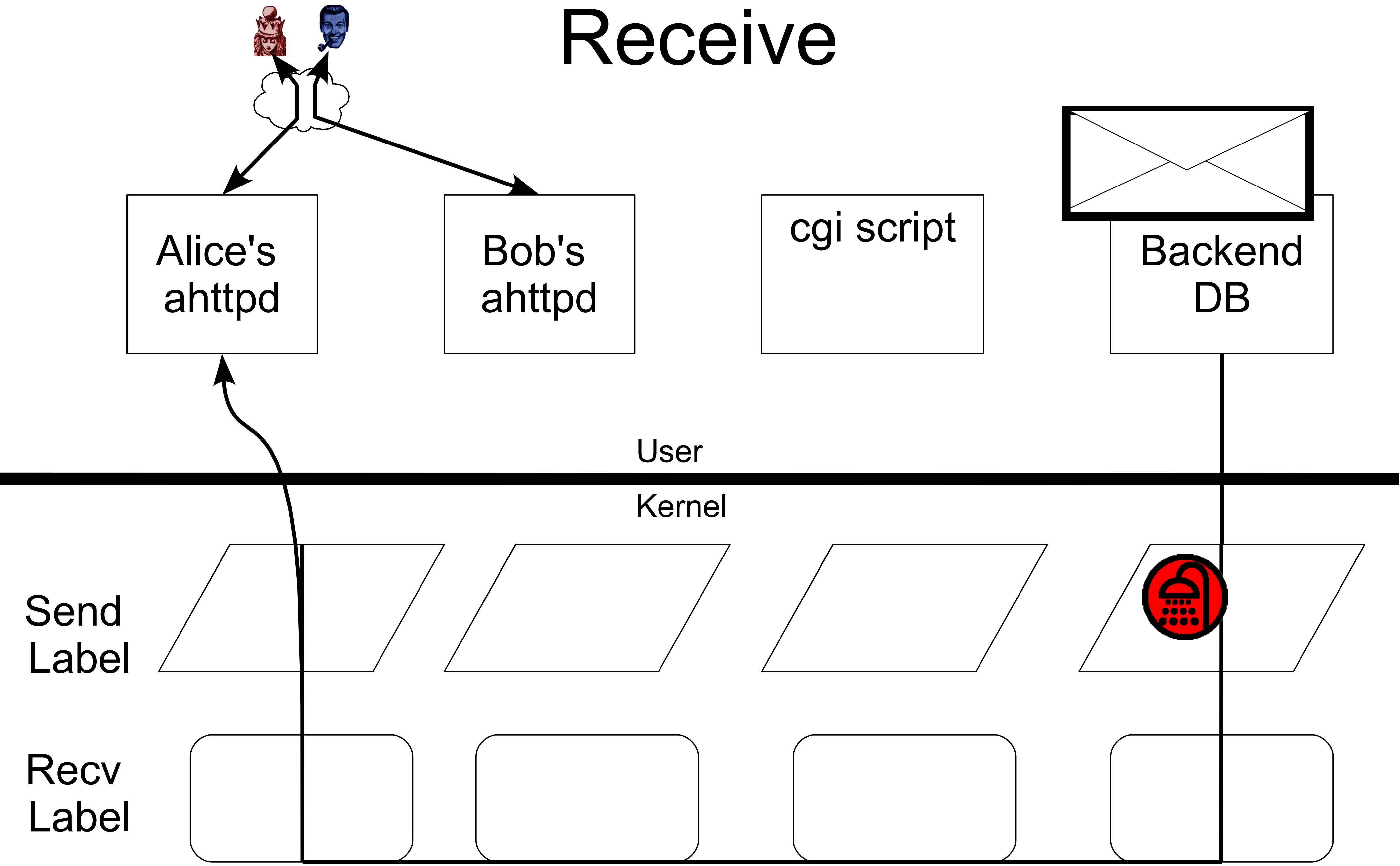


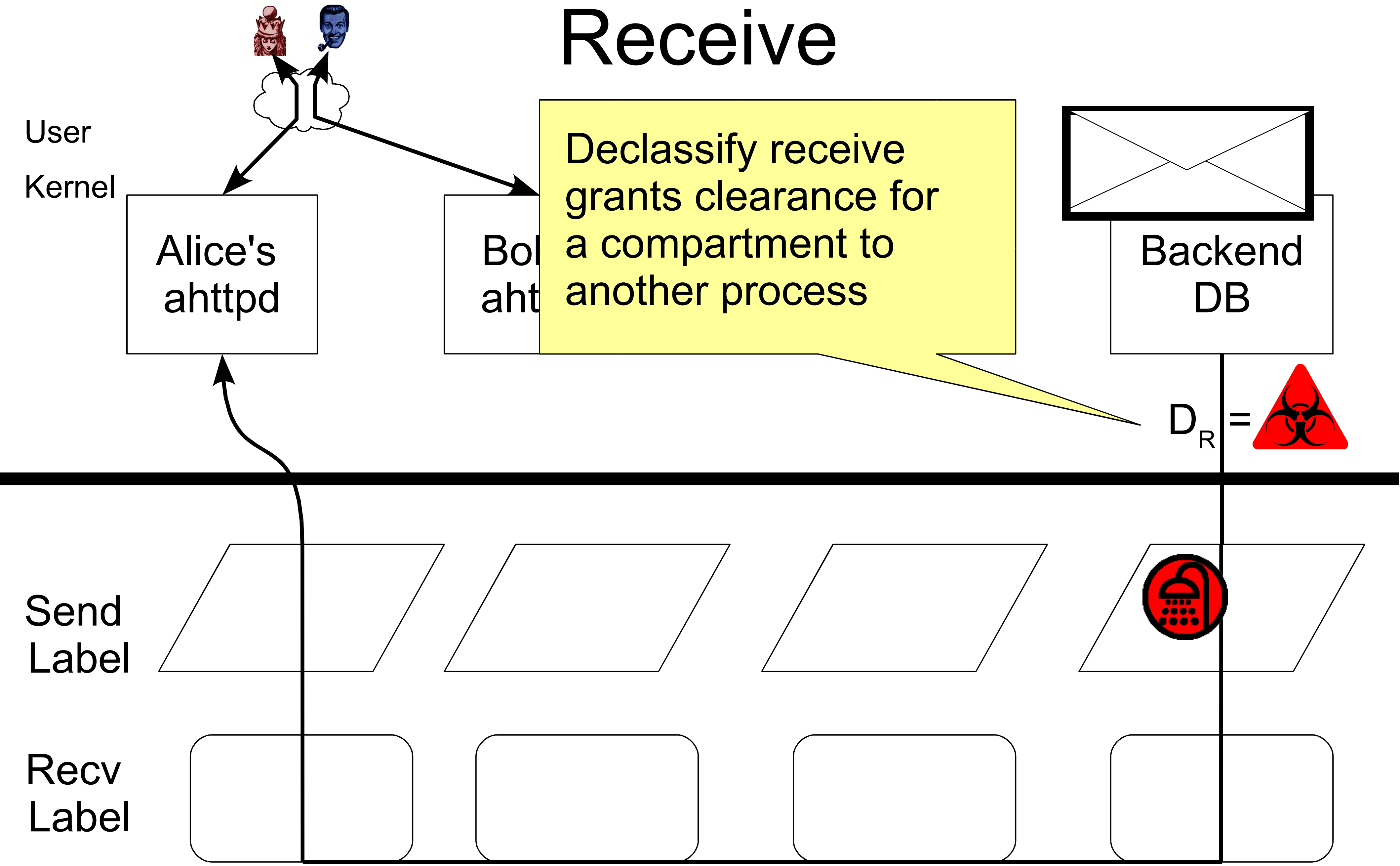
Declassify
Receive



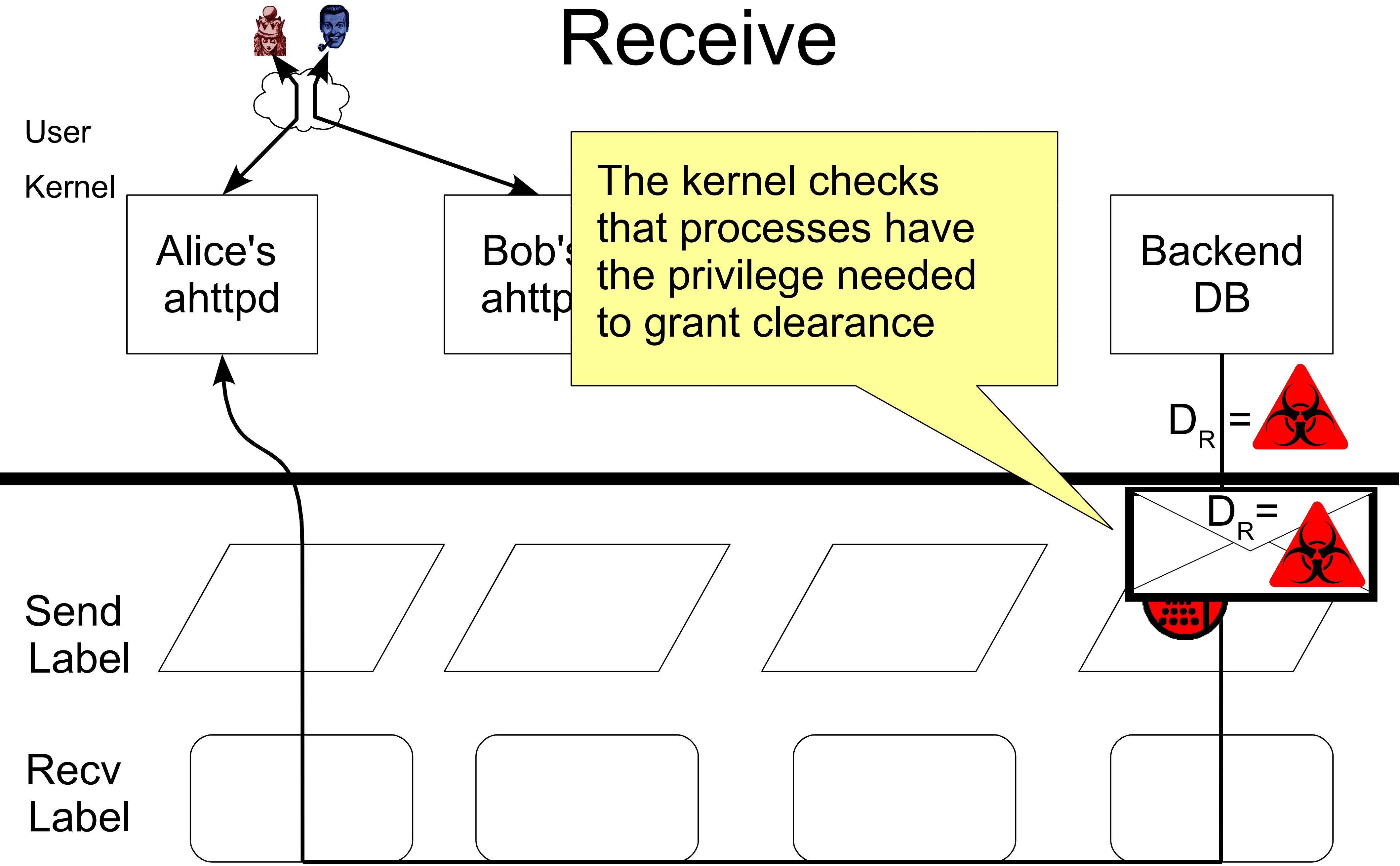
Optional Labels

- Process can attach optional (discretionary) labels to messages
  - C_S – Contaminate Send
  - D_R – Declassify Receive
  - D_S – Declassify Send
  - V – Verify

Declassify Receive



Declassify Receive



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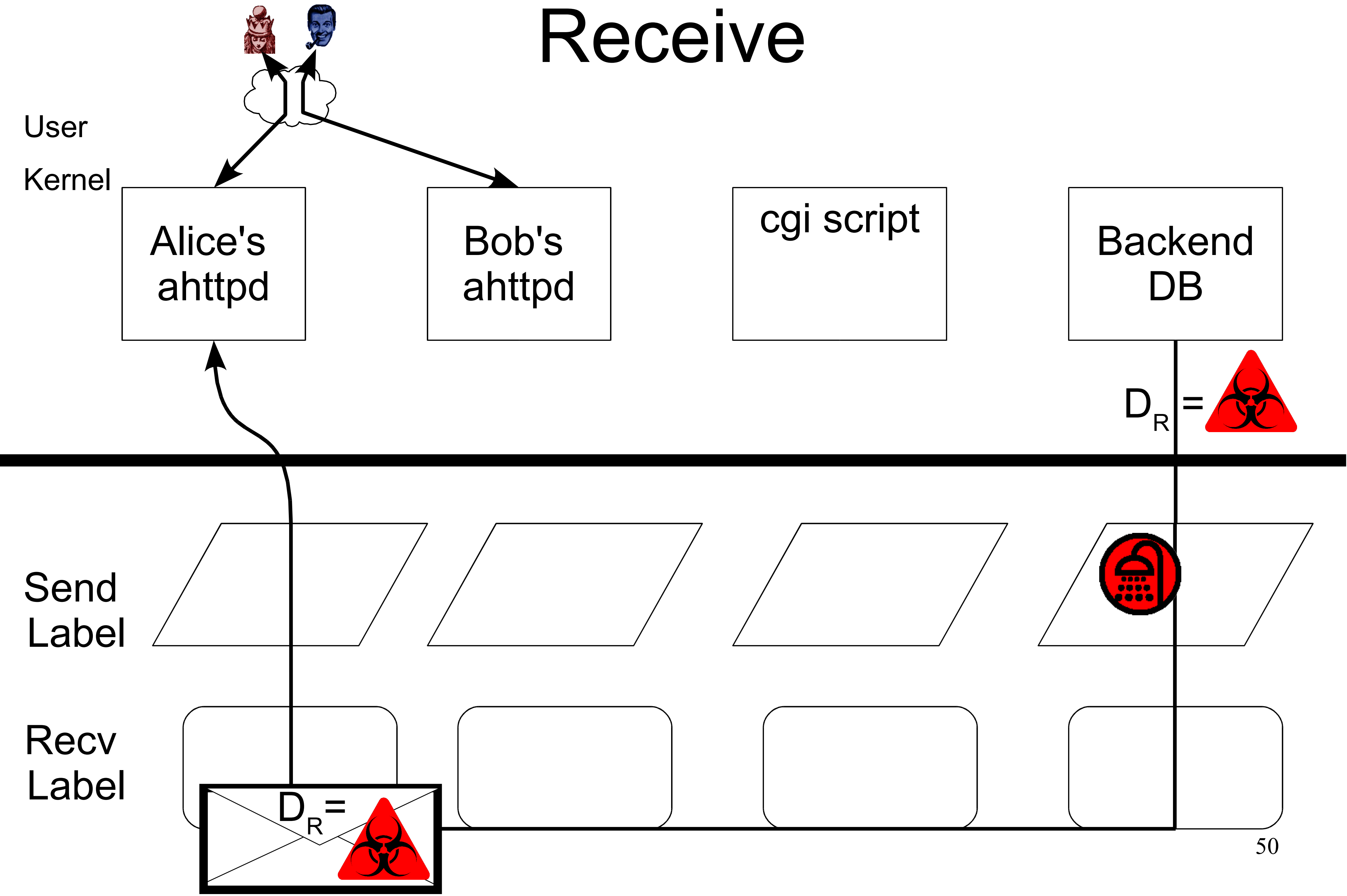

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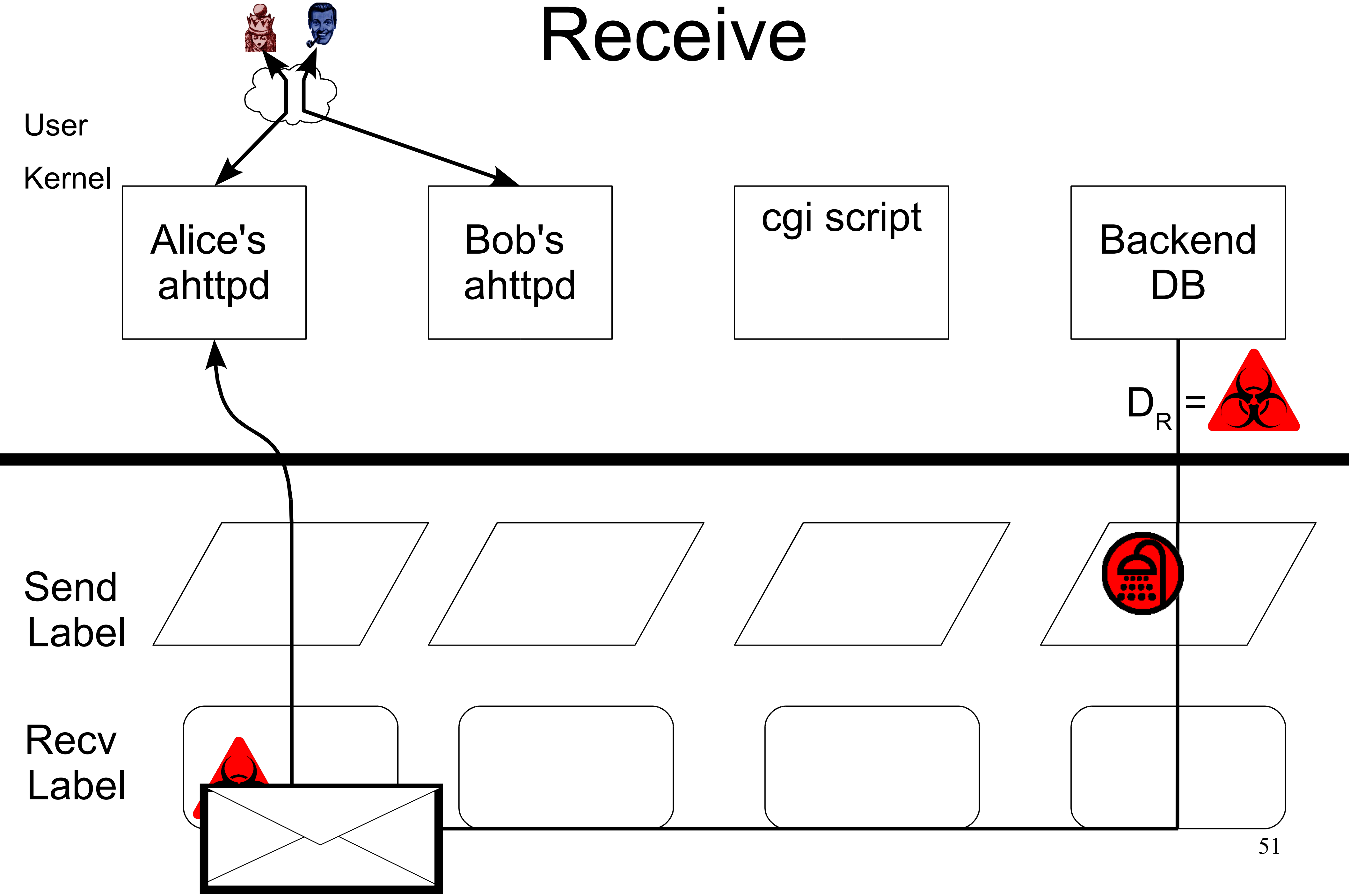

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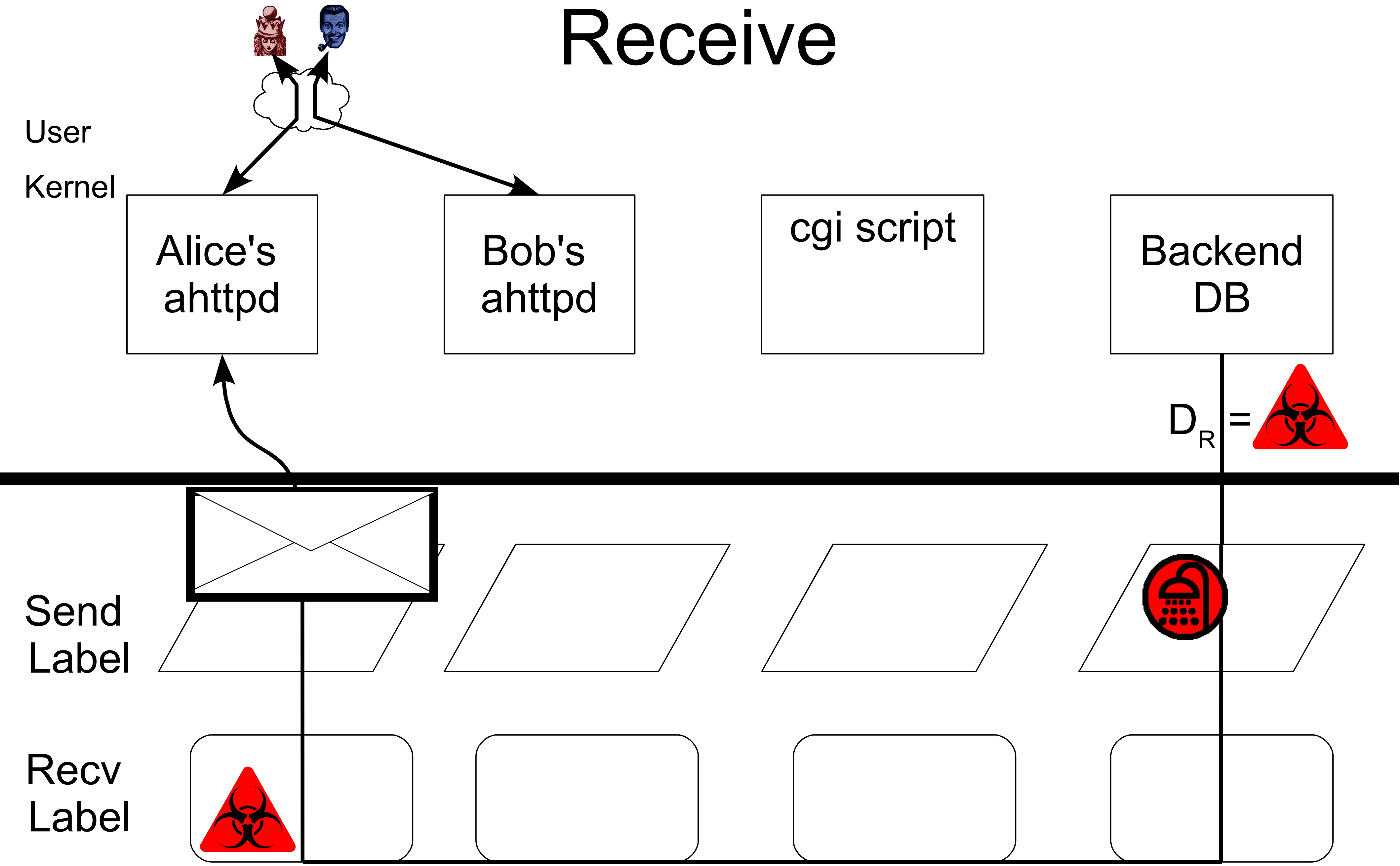

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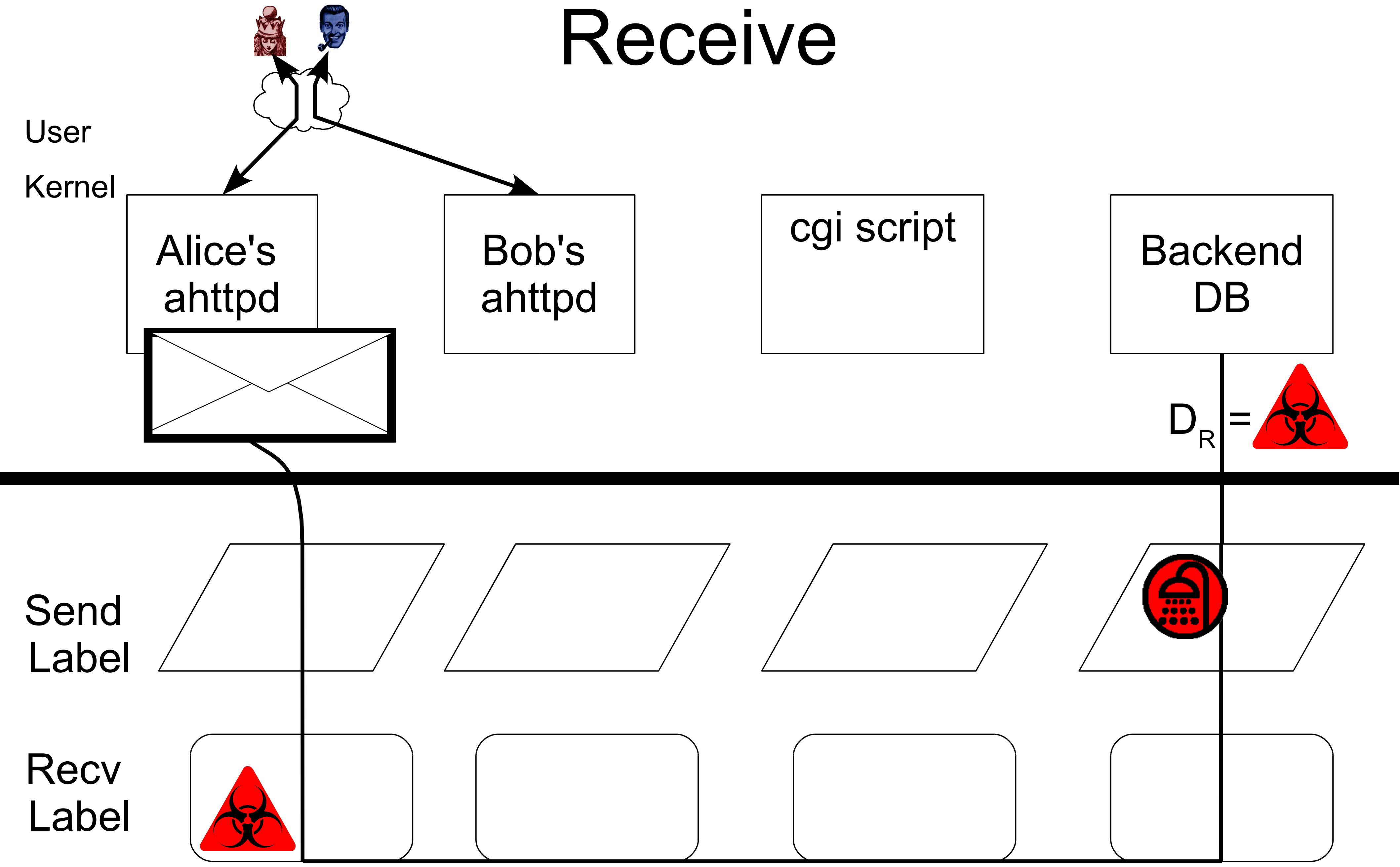
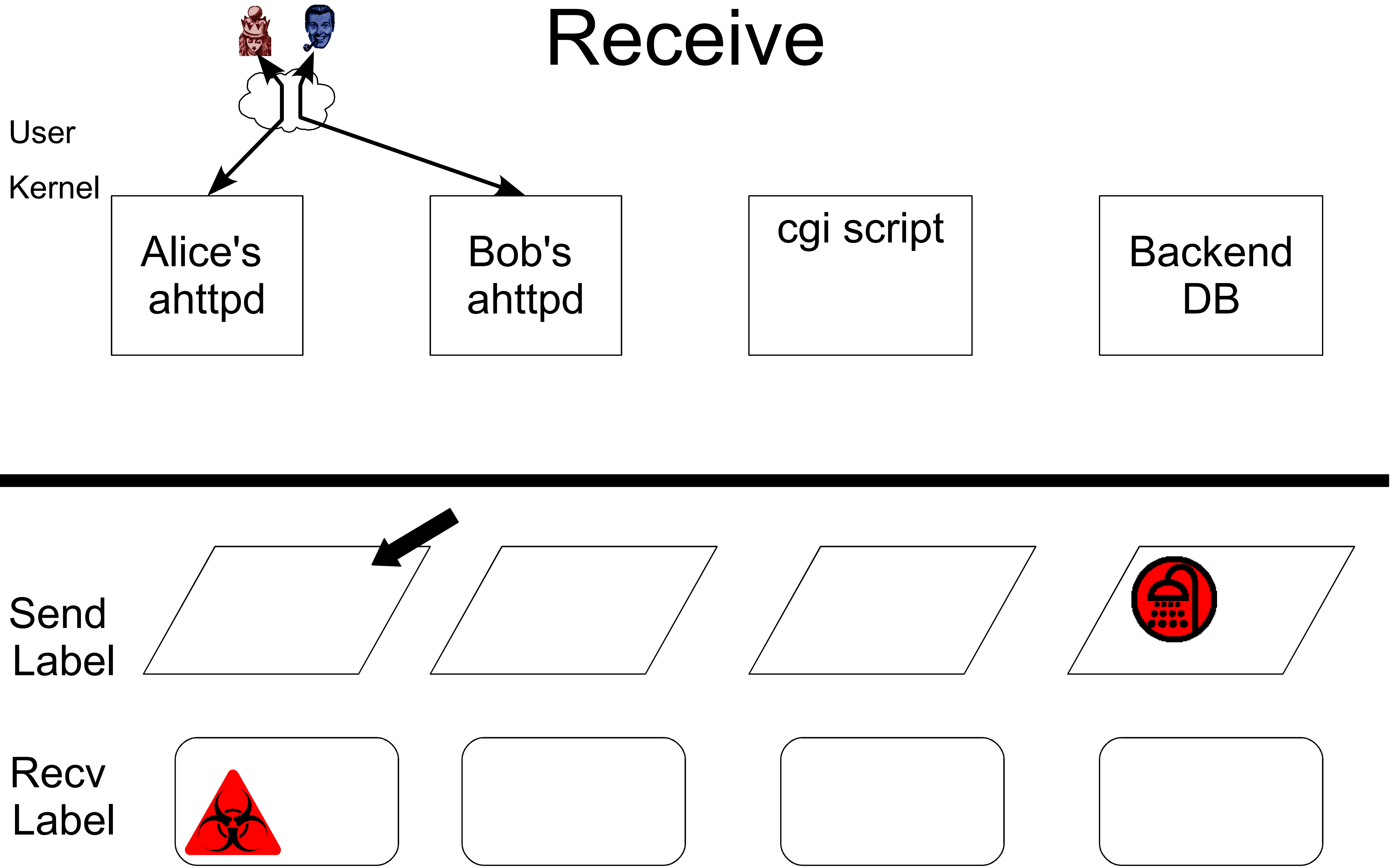
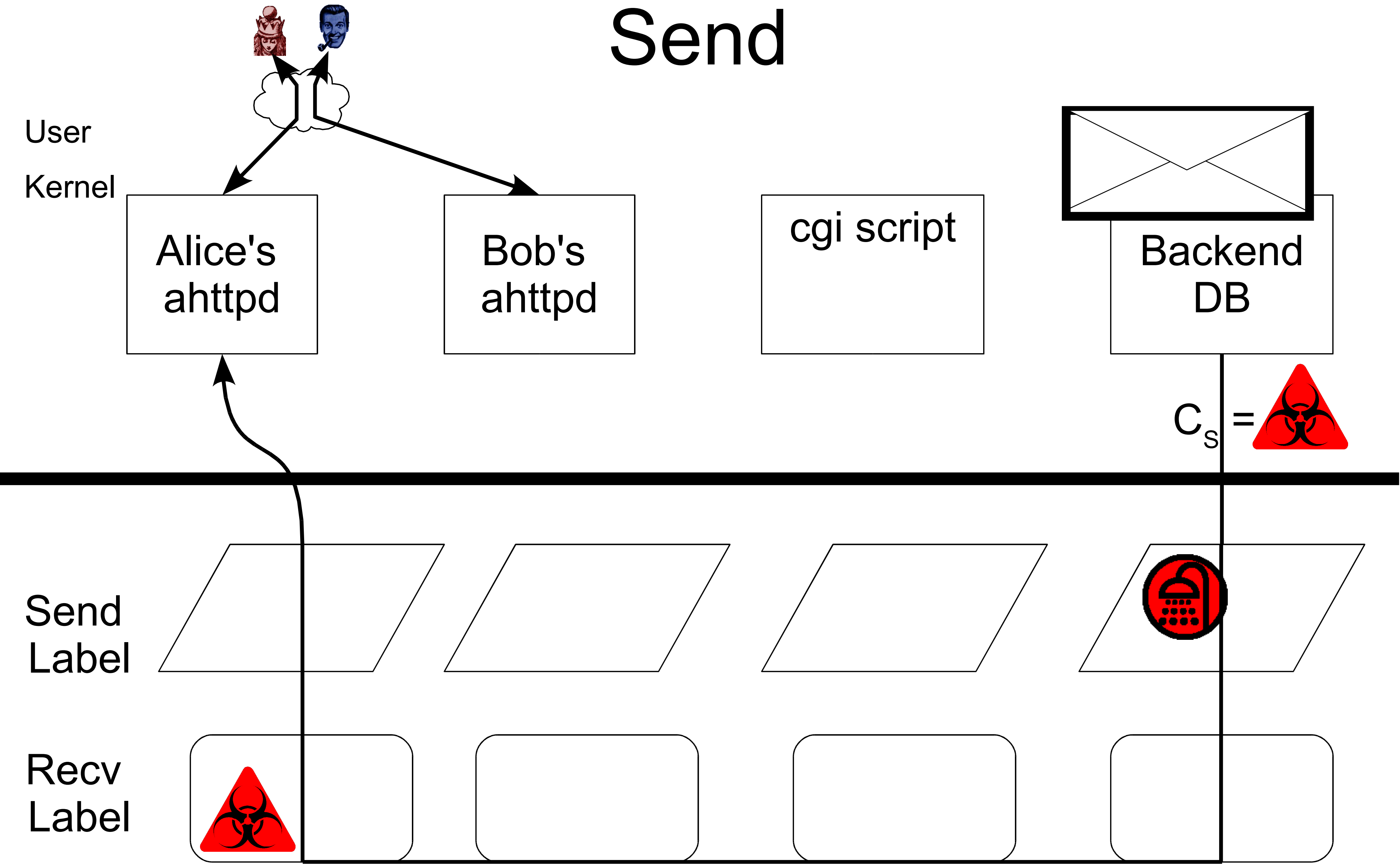


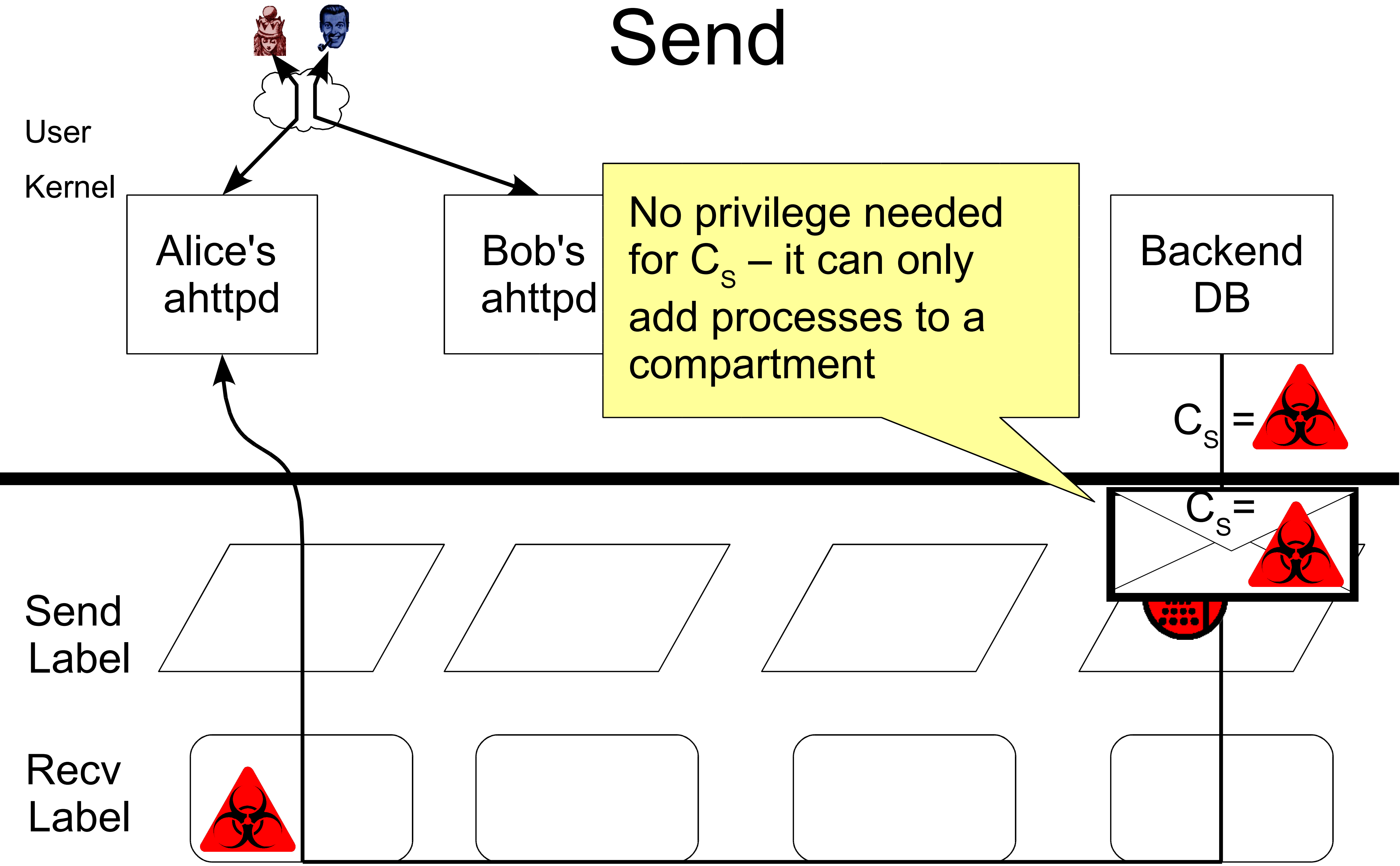
Declassify Receive



Contaminate Send



Contaminate Send



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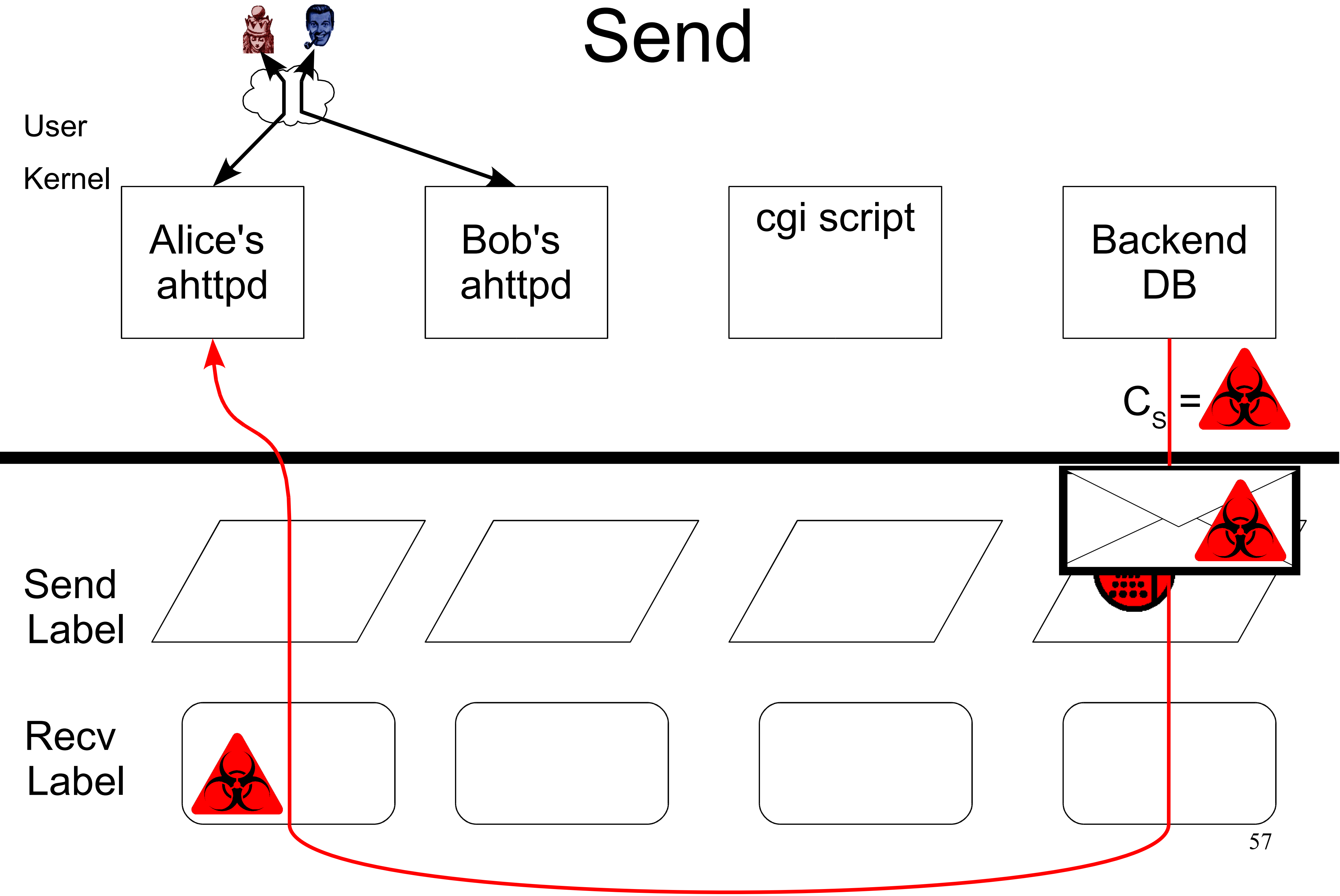
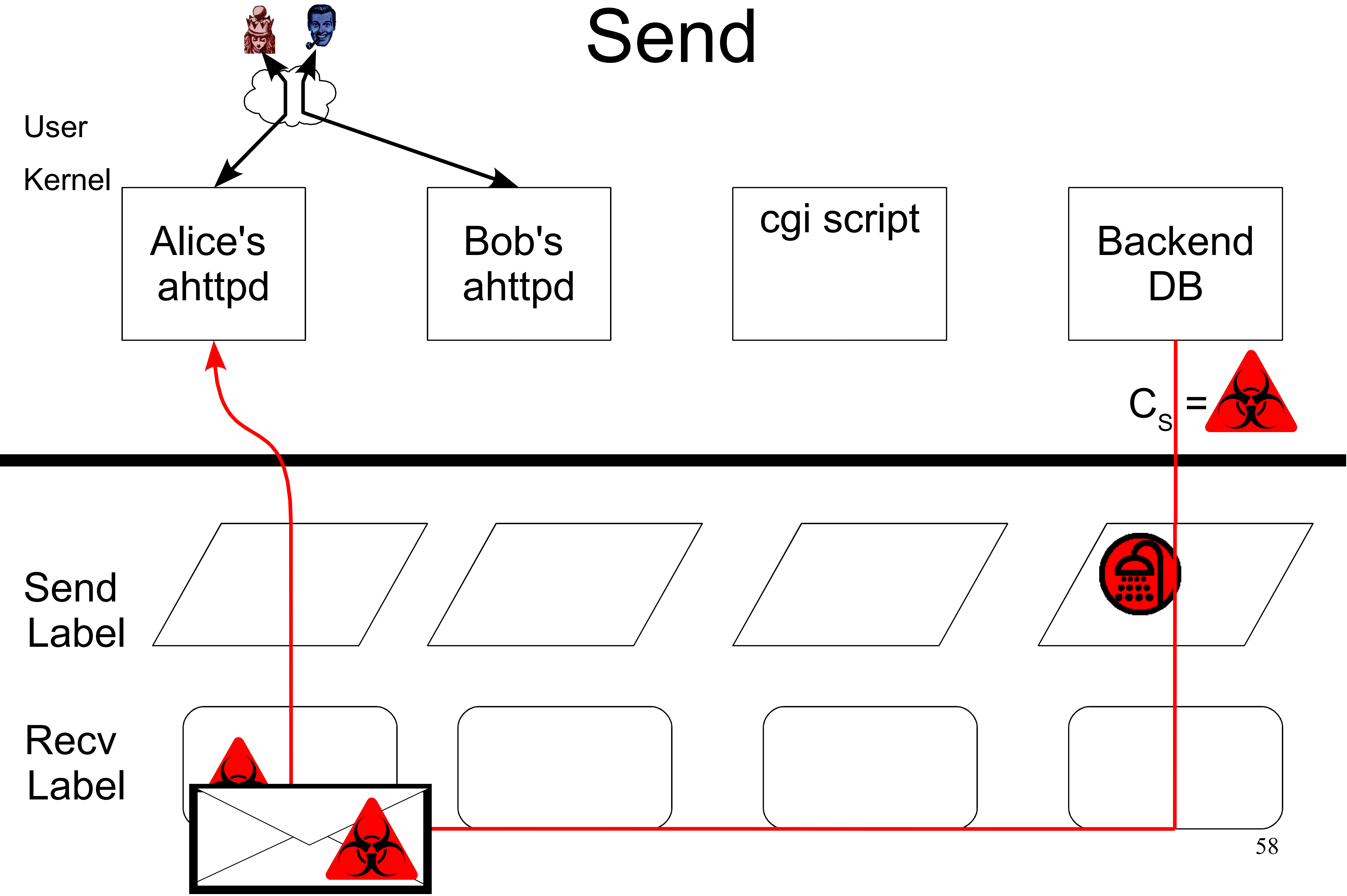
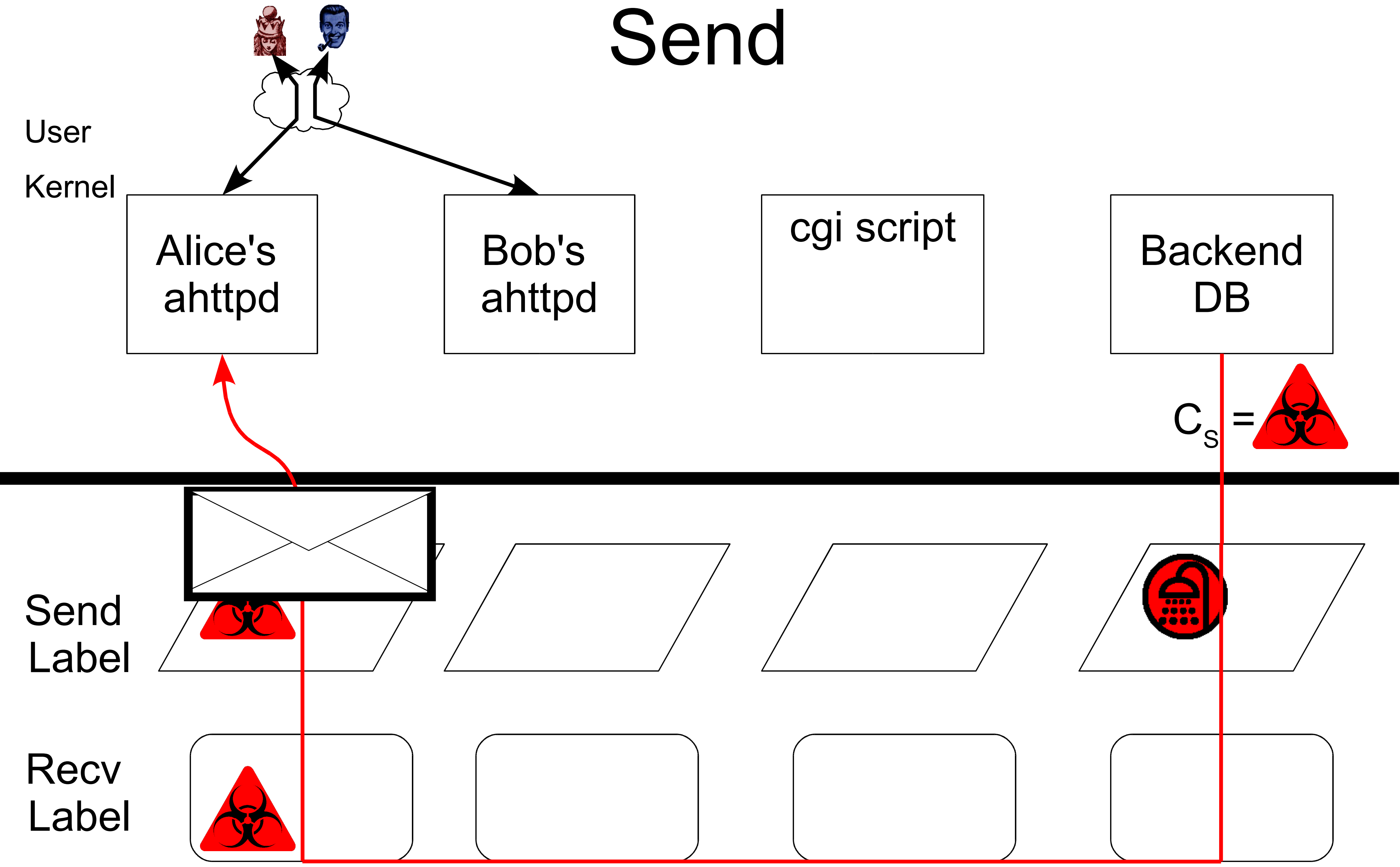


Contaminate Send



Contaminate Send



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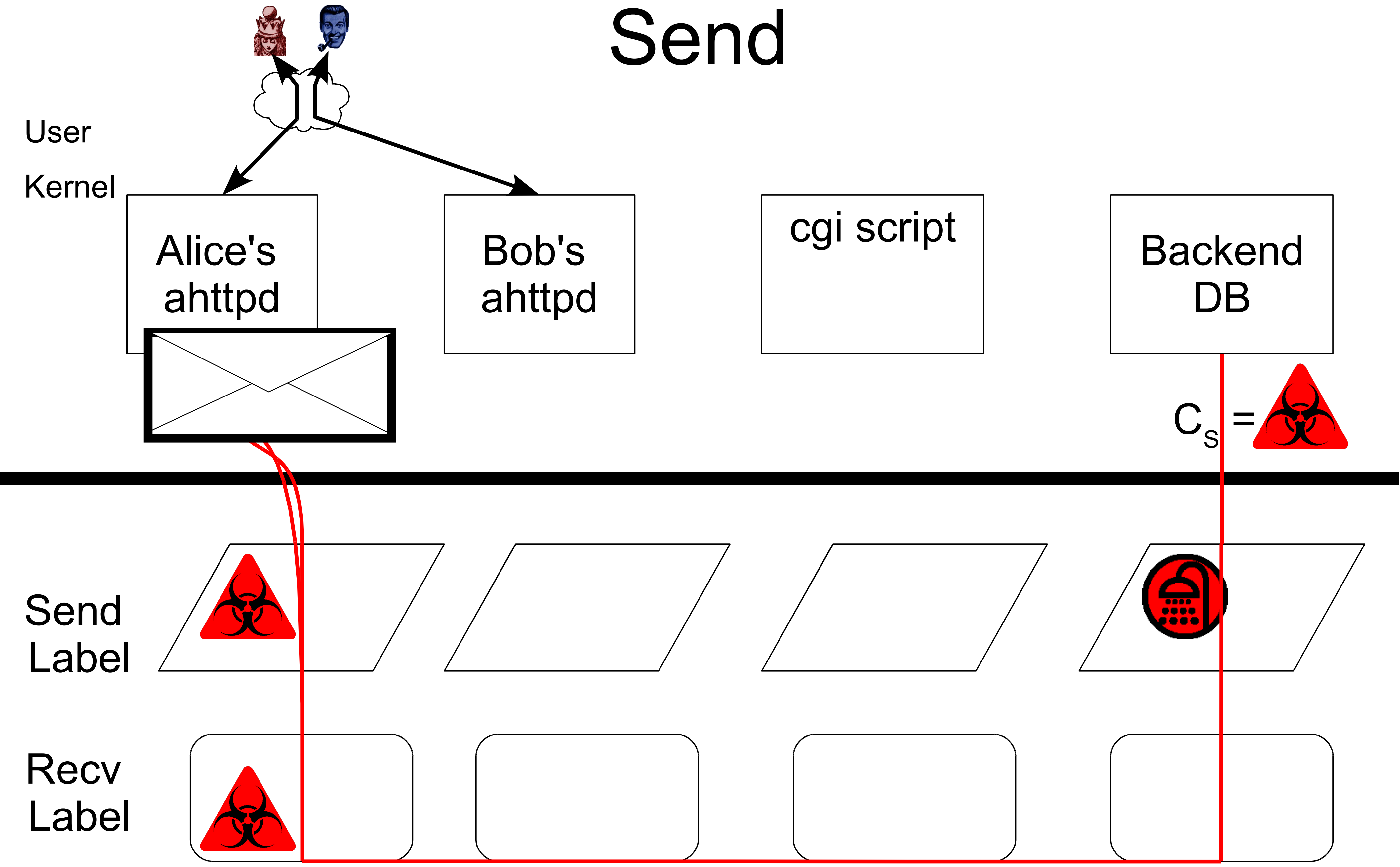
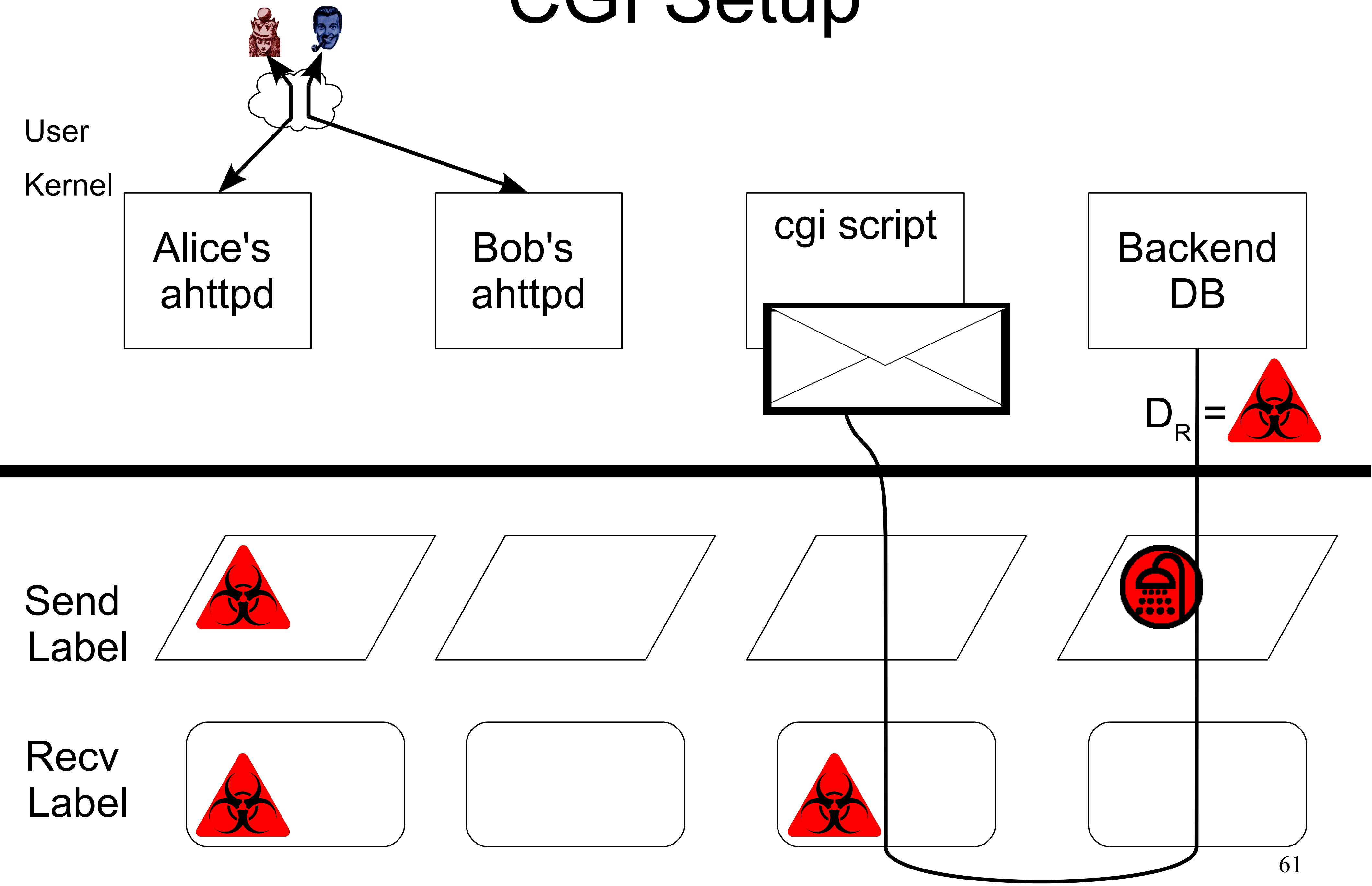
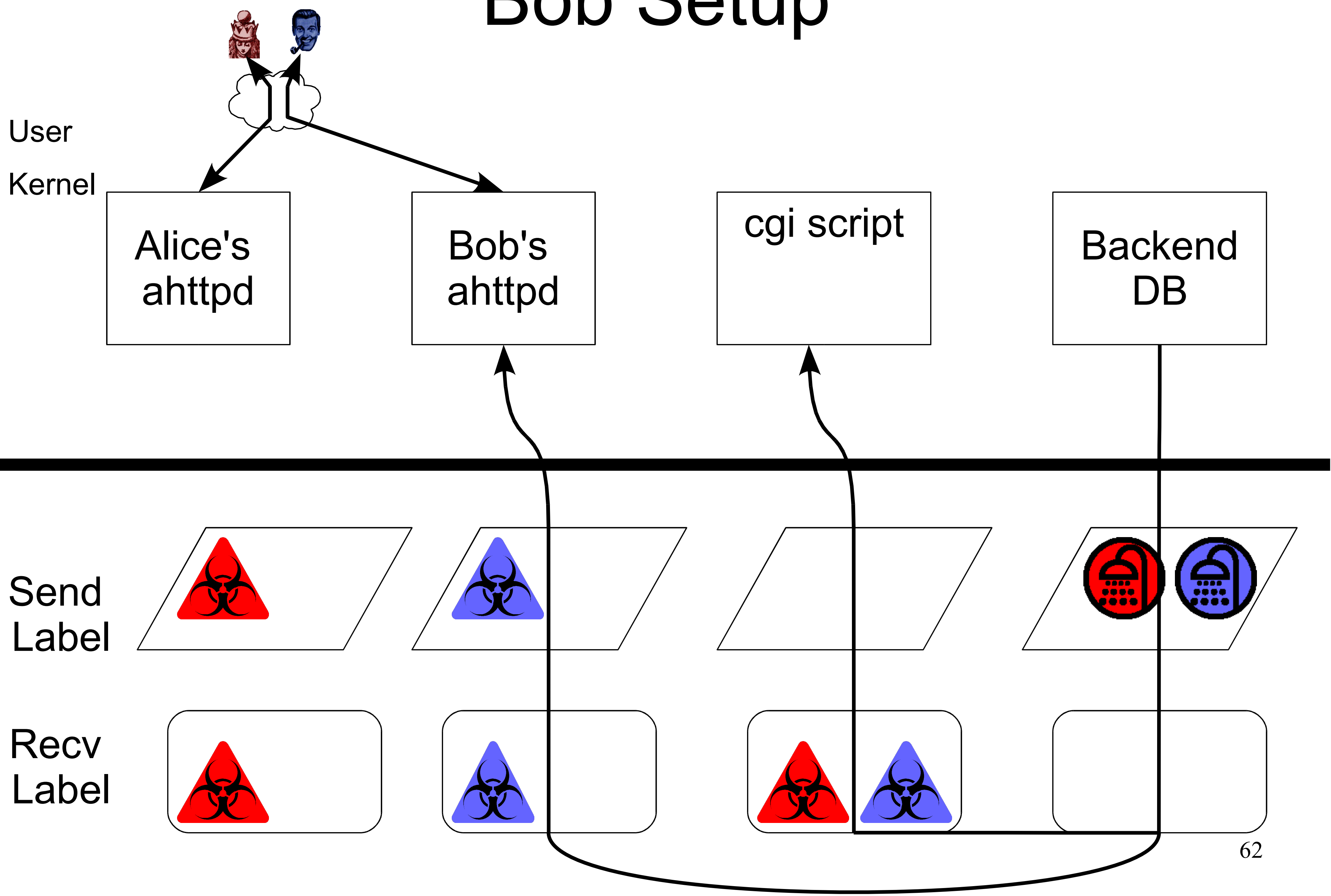


CGI Setup



User
Kernel
Alice's ahttpd
Bob's ahttpd
cgi script
Backend DB
D_R =
Send Label
Recv Label

Bob Setup



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Kernel
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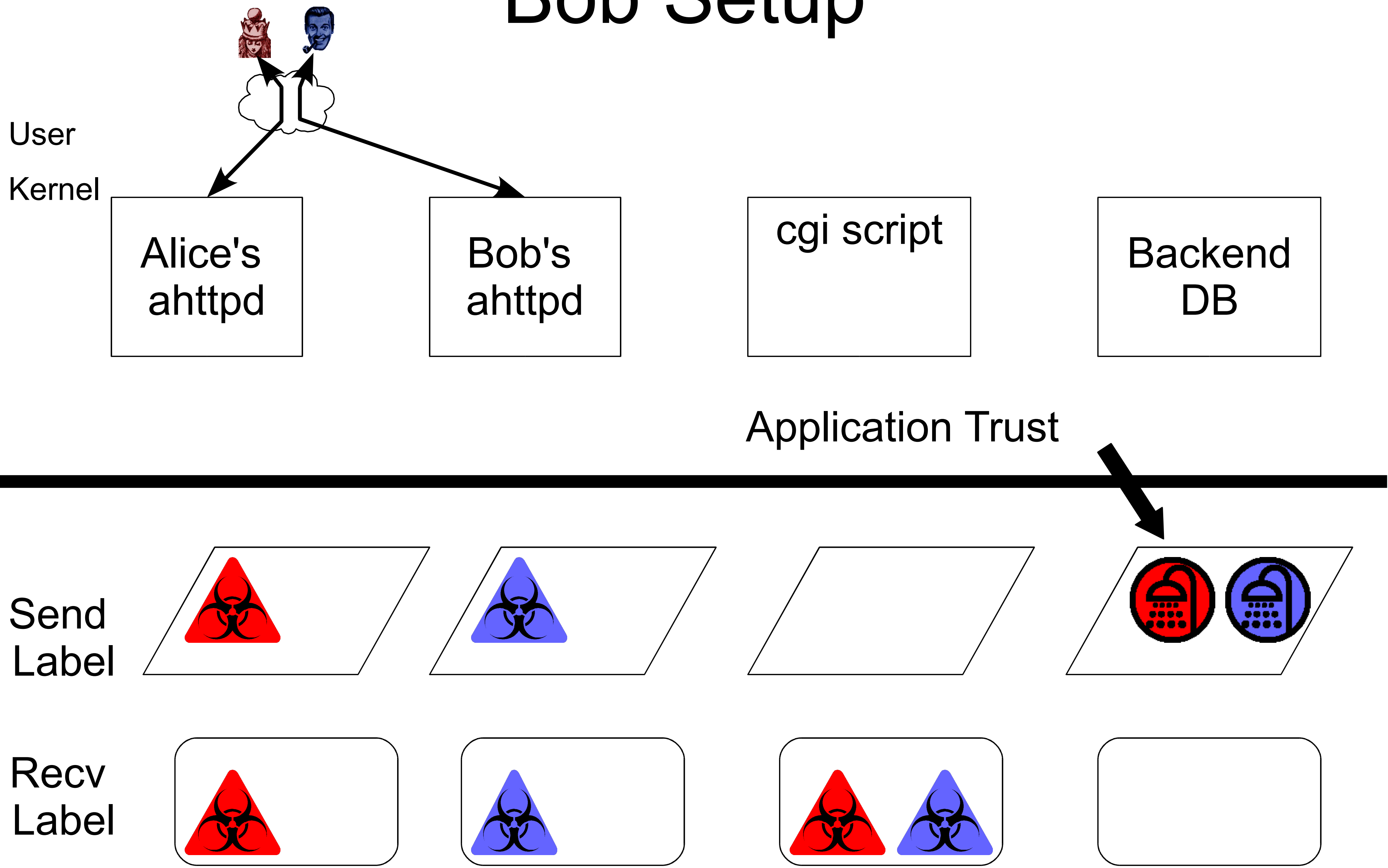
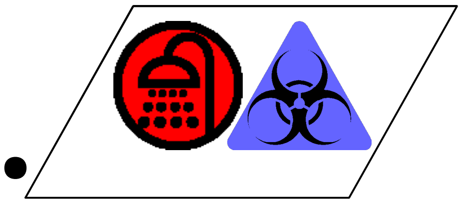
Bob Setup


User
Kernel
Alice's ahttpd
Bob's ahttpd
cgi script
Backend DB
Application Trust
Send Label
Recv Label

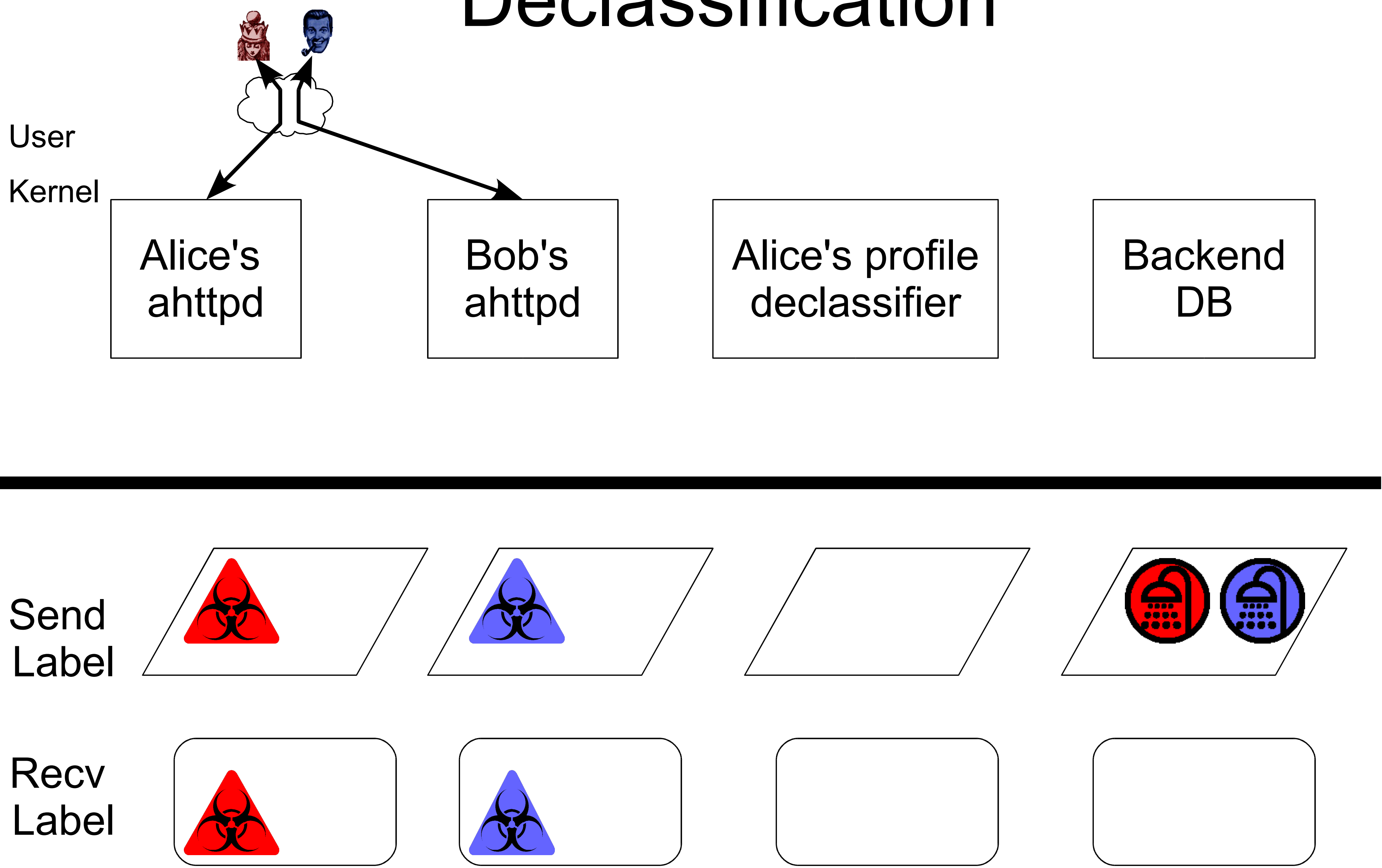
Label Implementation

- Contamination & Privilege = Label level (*, 0-3)
-  = {A *, B 3, 1}
- A & B are compartment names
- Trailing 1 = Neutral in all other compartments

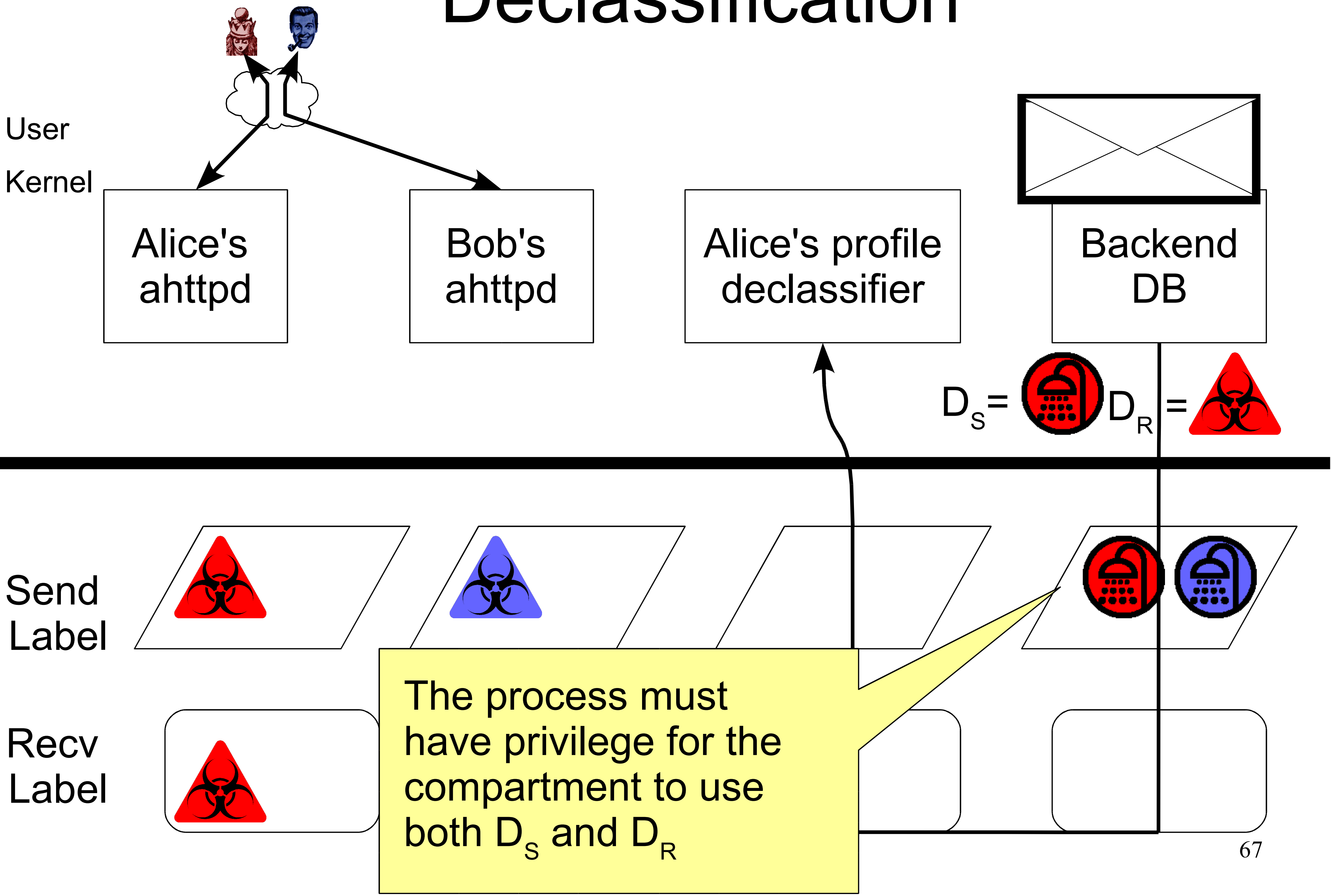
Declassification

- Information flow control keeps users data completely disjoint
- Alice wants to export **some** of her data, like her profile
  - But **all** her data is in her compartment
- How can she safely declassify her data?
- Alice must trust all processes that can do so
- To minimize declassification bugs, we build declassifiers as simple, single purpose programs

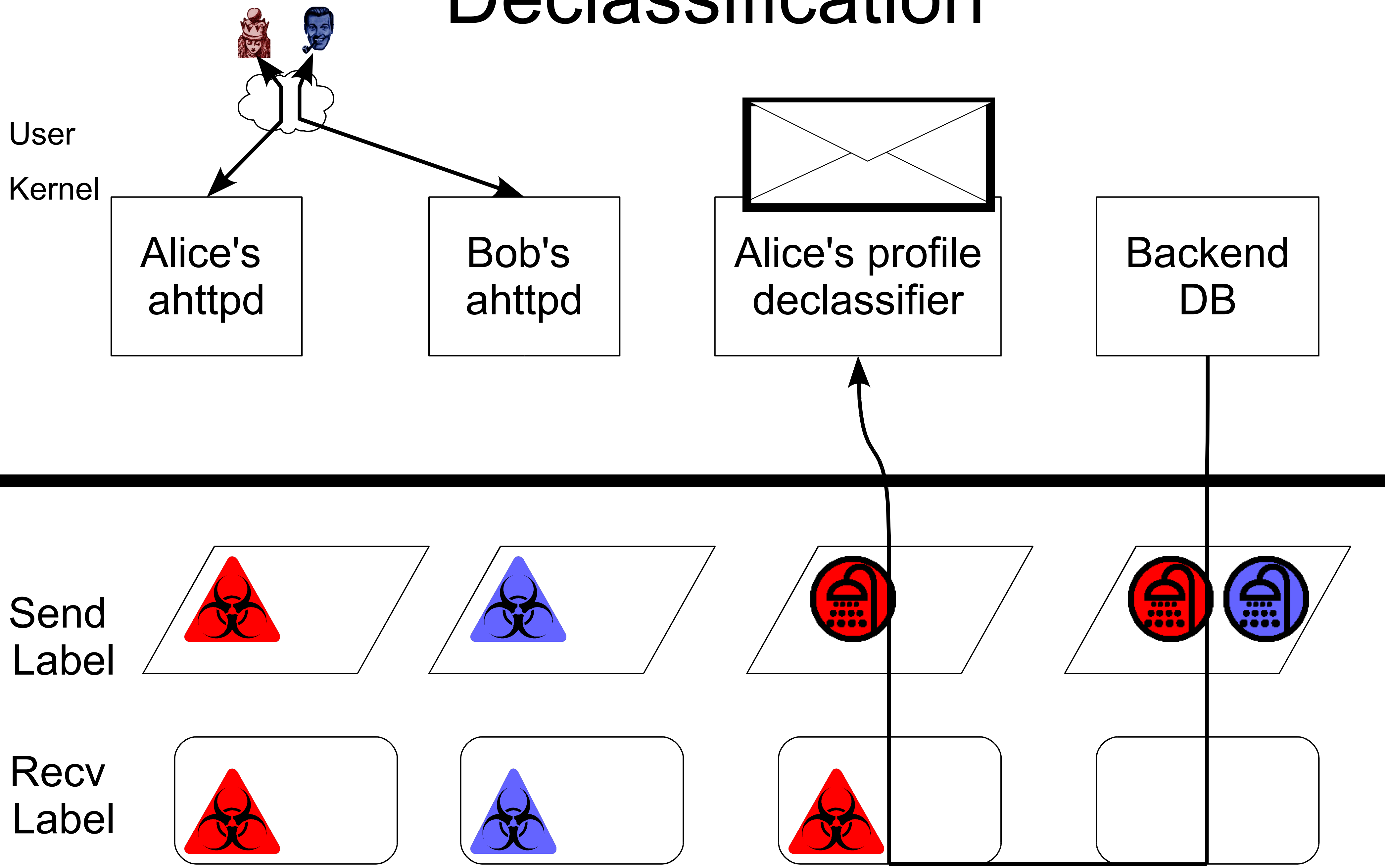
Declassification



Declassification



Declassification



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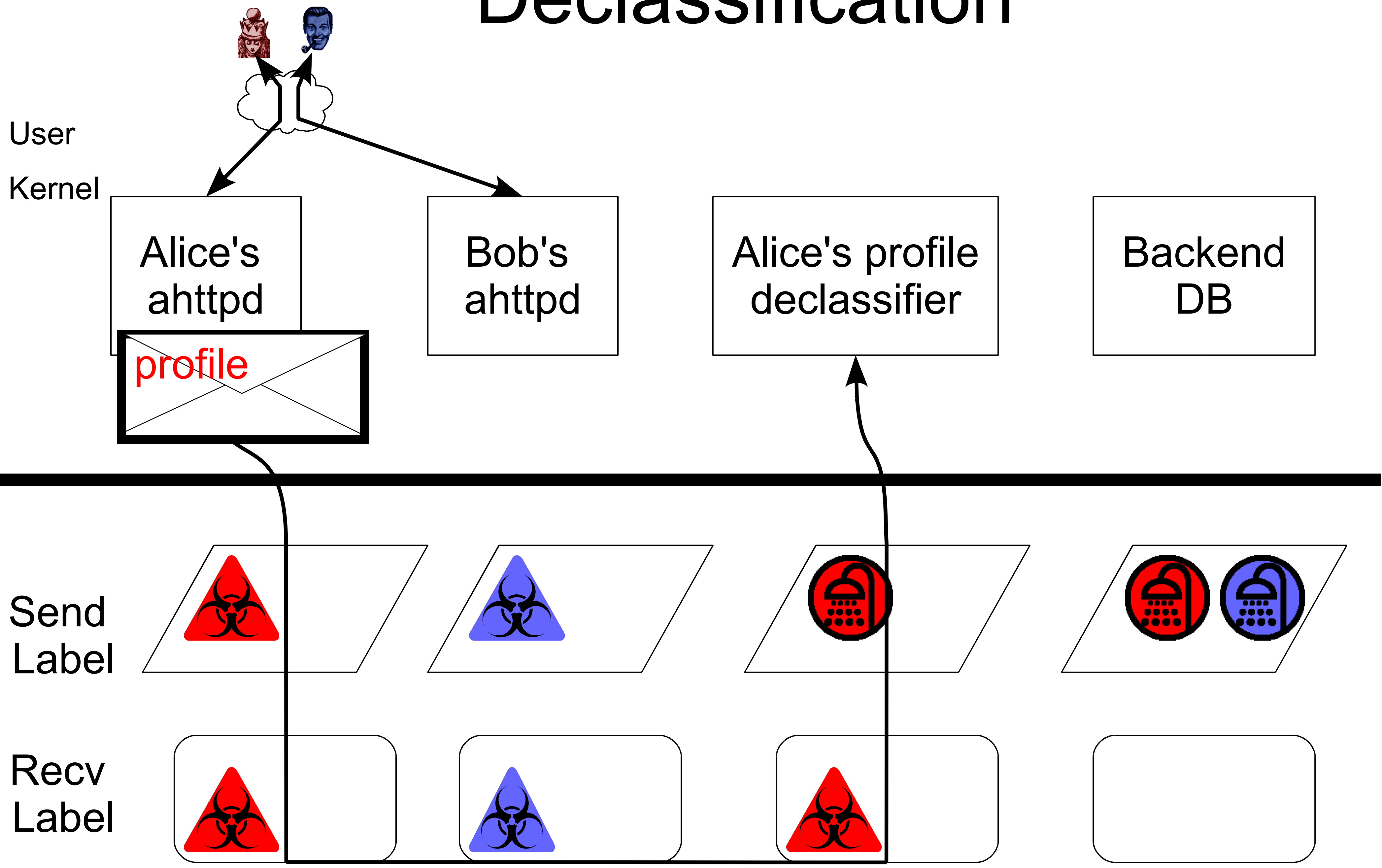

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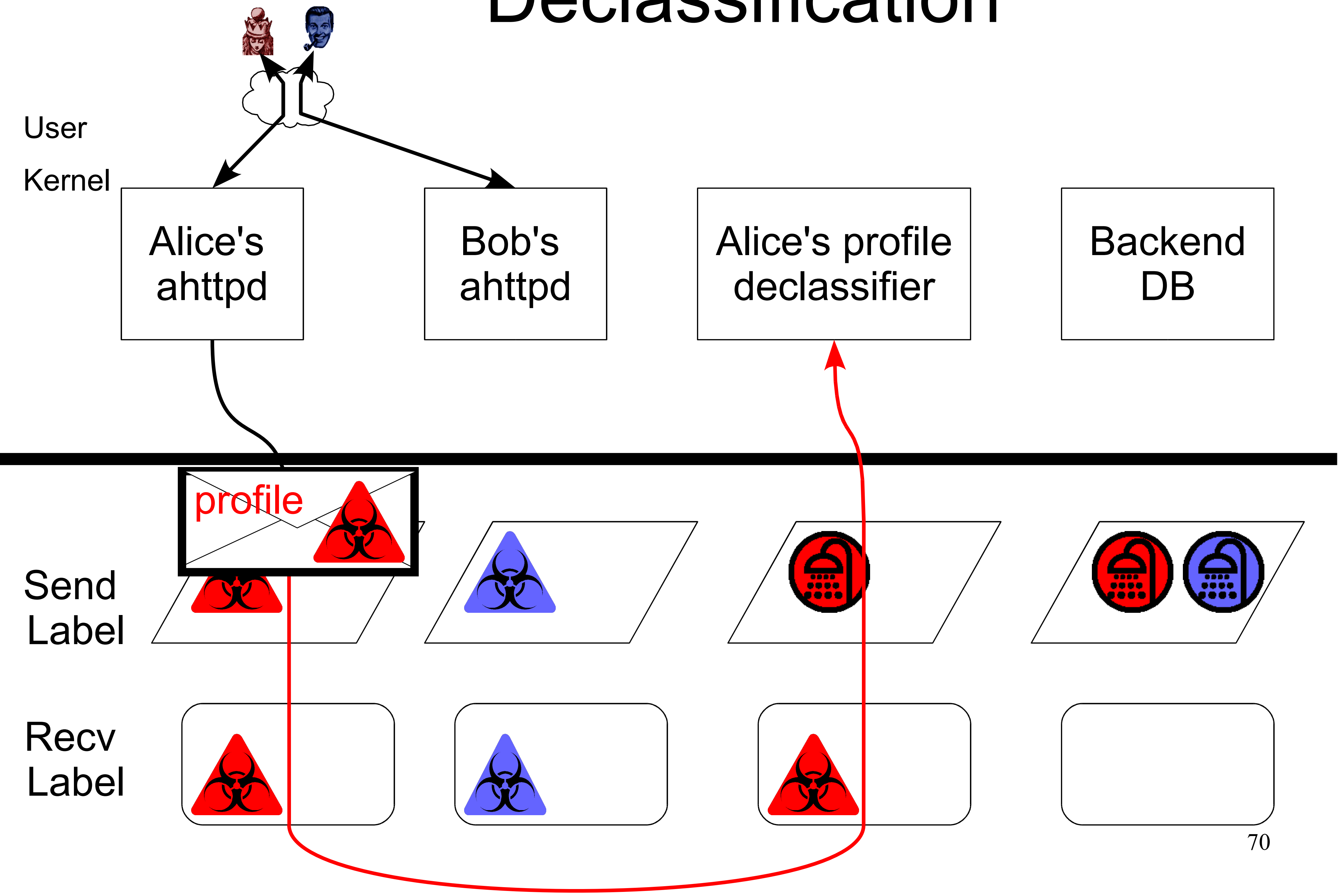
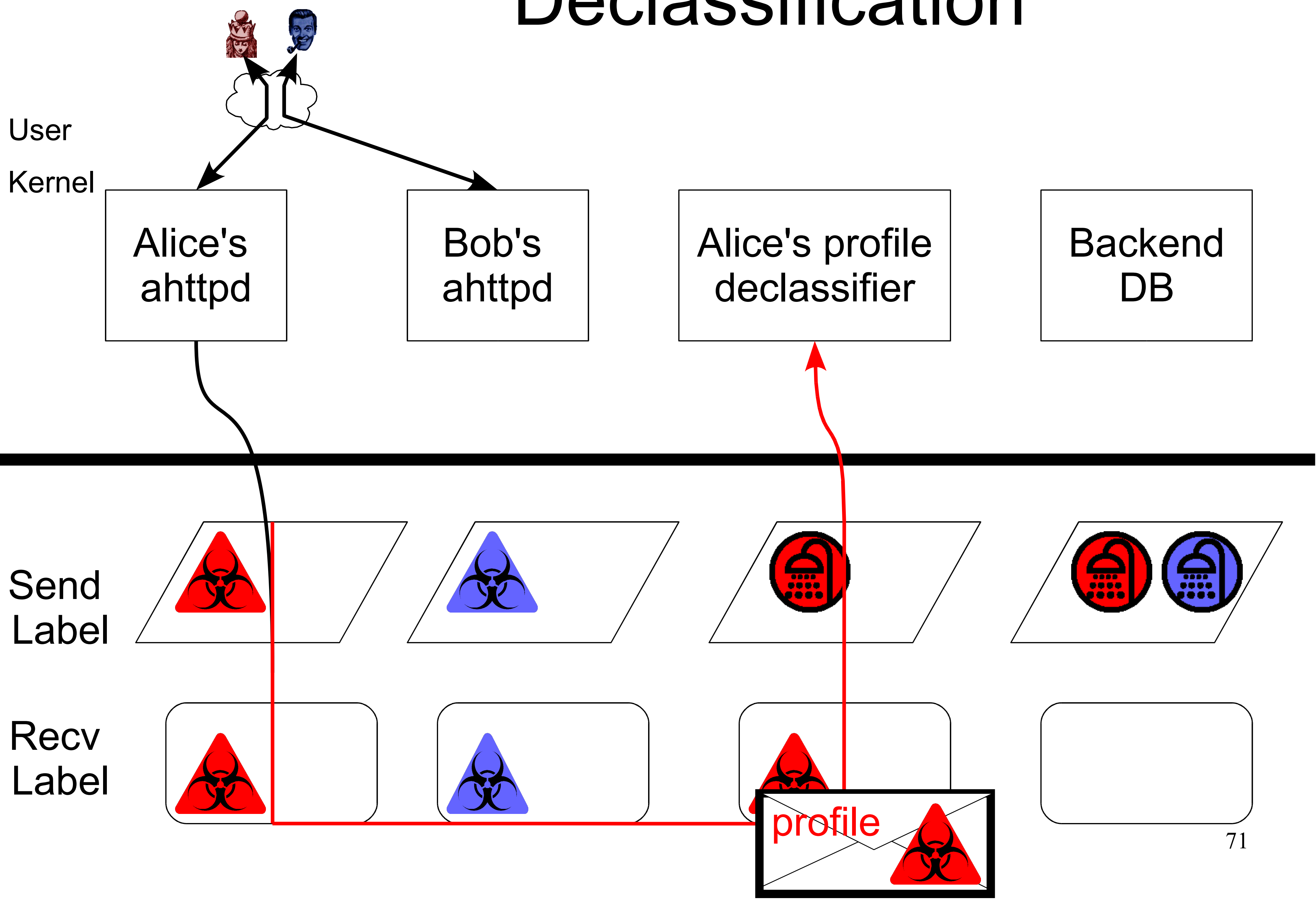
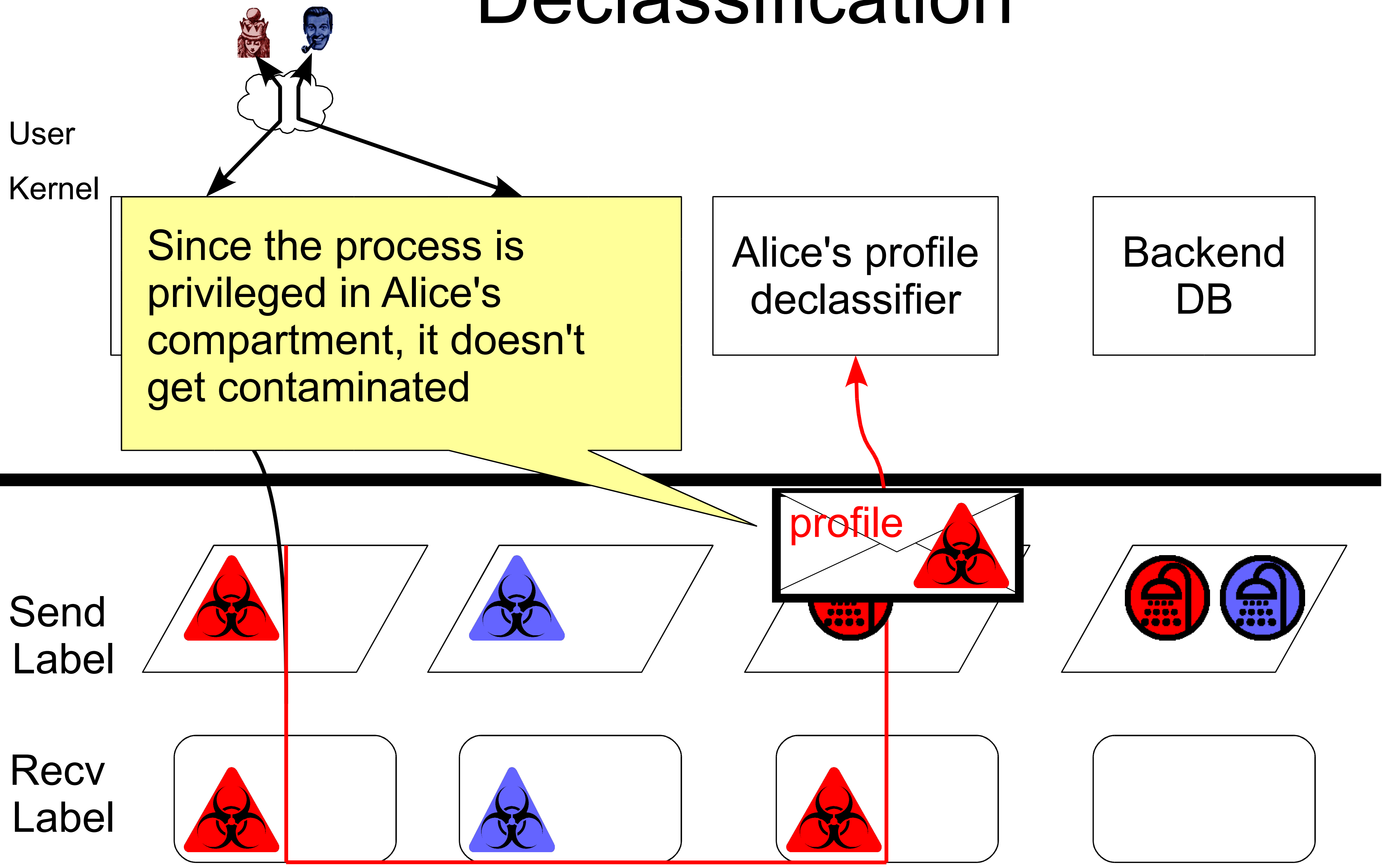


Declassification



Declassification



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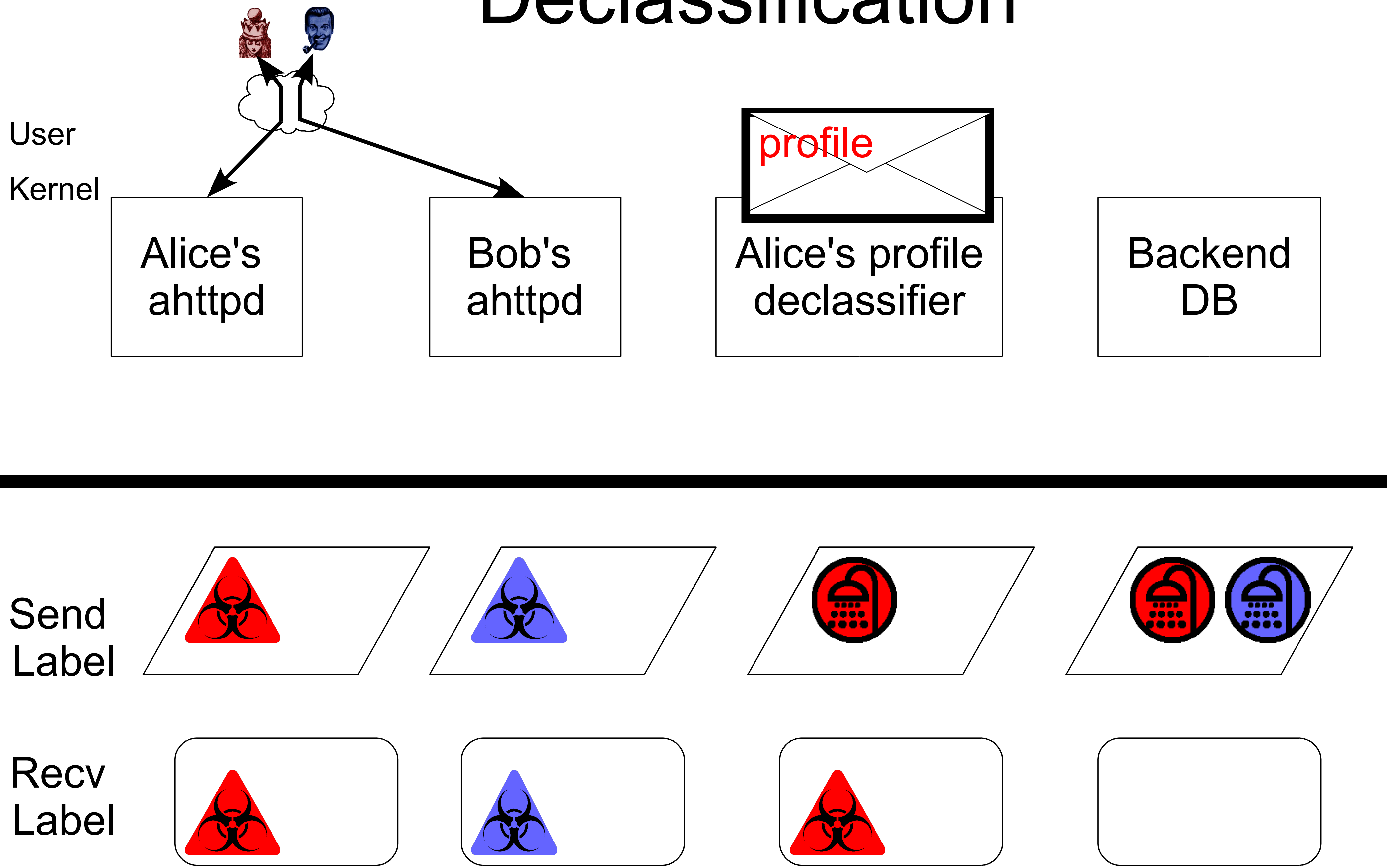


Other Label Features

- Verify label on messages
  - Allows a process to prove it has labels at specific levels
- Integrity tracking
  - Enabled by level 0
- Different default level for send & receive labels
  - Enables interesting isolation policies

Preventing Contamination

- Ports
  - Associated with receive label
  - Verification imposed by receiver
  - Deny decontamination of receive labels beyond certain point
  - Receiver can grant rights to processes to send
  - Prevents arbitrary processes from sending to it

Combating Process Over-Contamination

- One process per user per service
  - Lots of heavy weight context switches
  - Lots of memory
- Combine processes to get one process per service?
  - Become too contaminated to function
  - Or **too** privileged
- Many processes are similar
- Programming style help?

Event Loop

```
while (1) {
    event = get_next_event();
    user = lookup_user(event);
    if (user not yet seen)
        user.state = create_state();
    process_event(event, user);
}
```

- State isolated to data structures
- Stack not used from event to event
- Execution state has nice preemption points

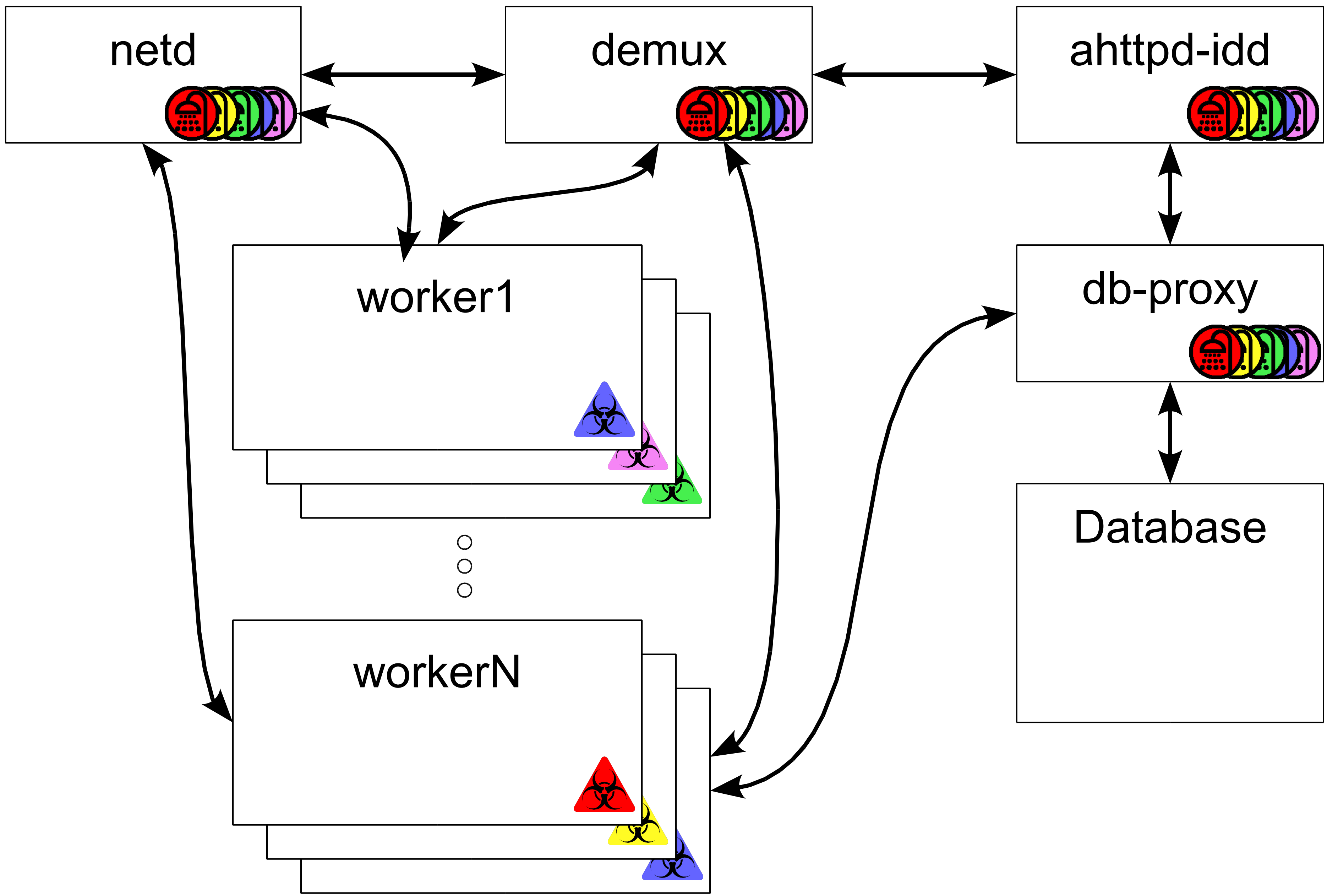
Event Process Abstraction

l

```
ep_checkpoint(&msg);
if (!state.initialized) {
    initialize_state(&state);
    state.reply = new_port();
}
process_message(&msg, &state);
ep_yield(); // revert to chkpointed memory
```

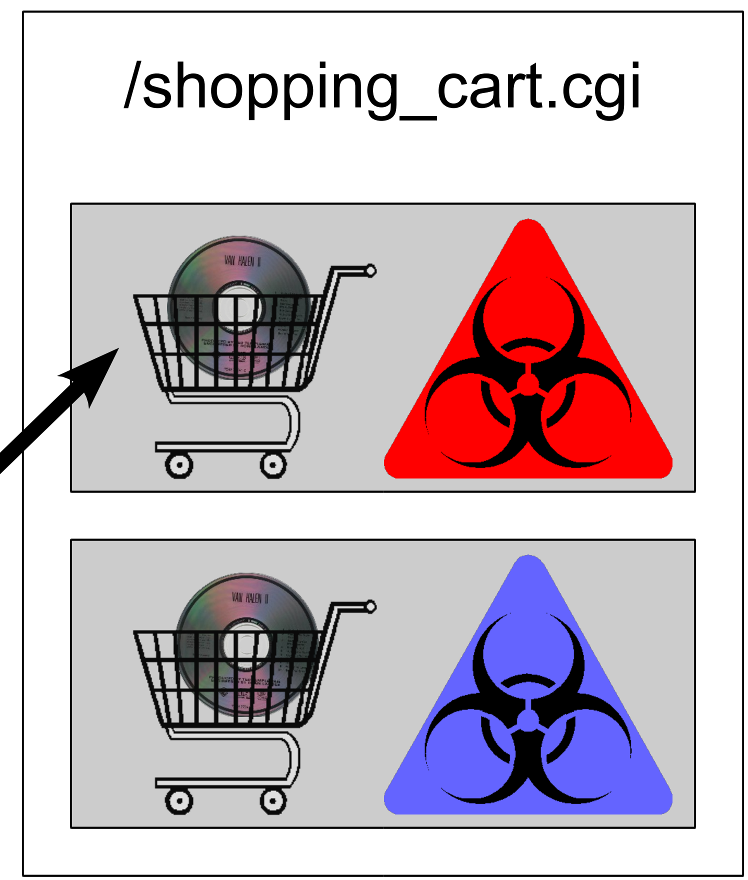
- Fork memory state for each new session
    - Memory isolation is the same as fork
    - Small differences anticipated, stored efficiently (diff)
- Event loop allows shared execution state
    - Allows light weight context switches

Web Server Architecture

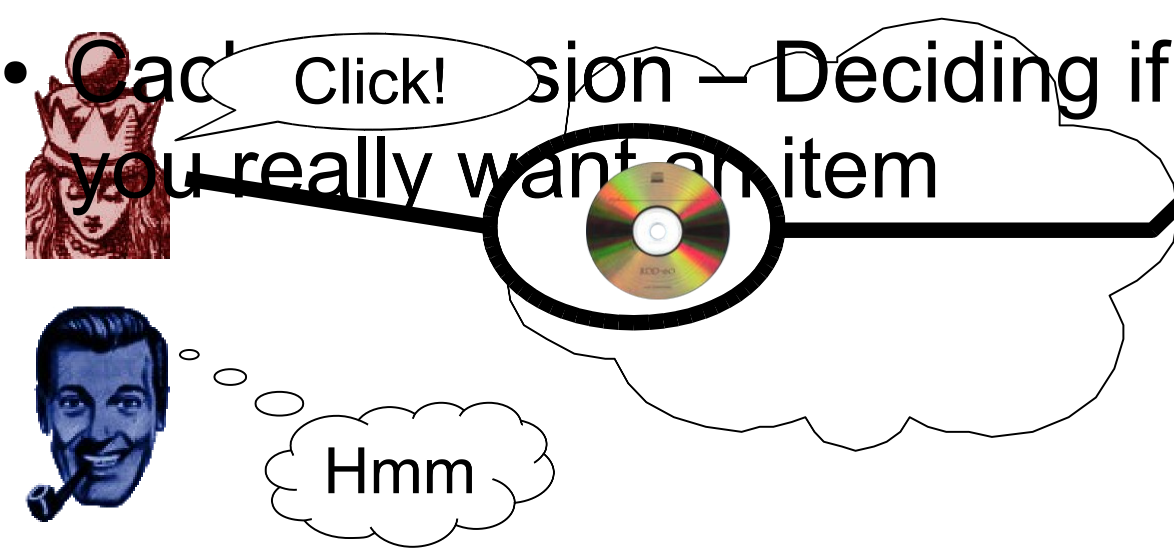


Experimental Setup – Memory

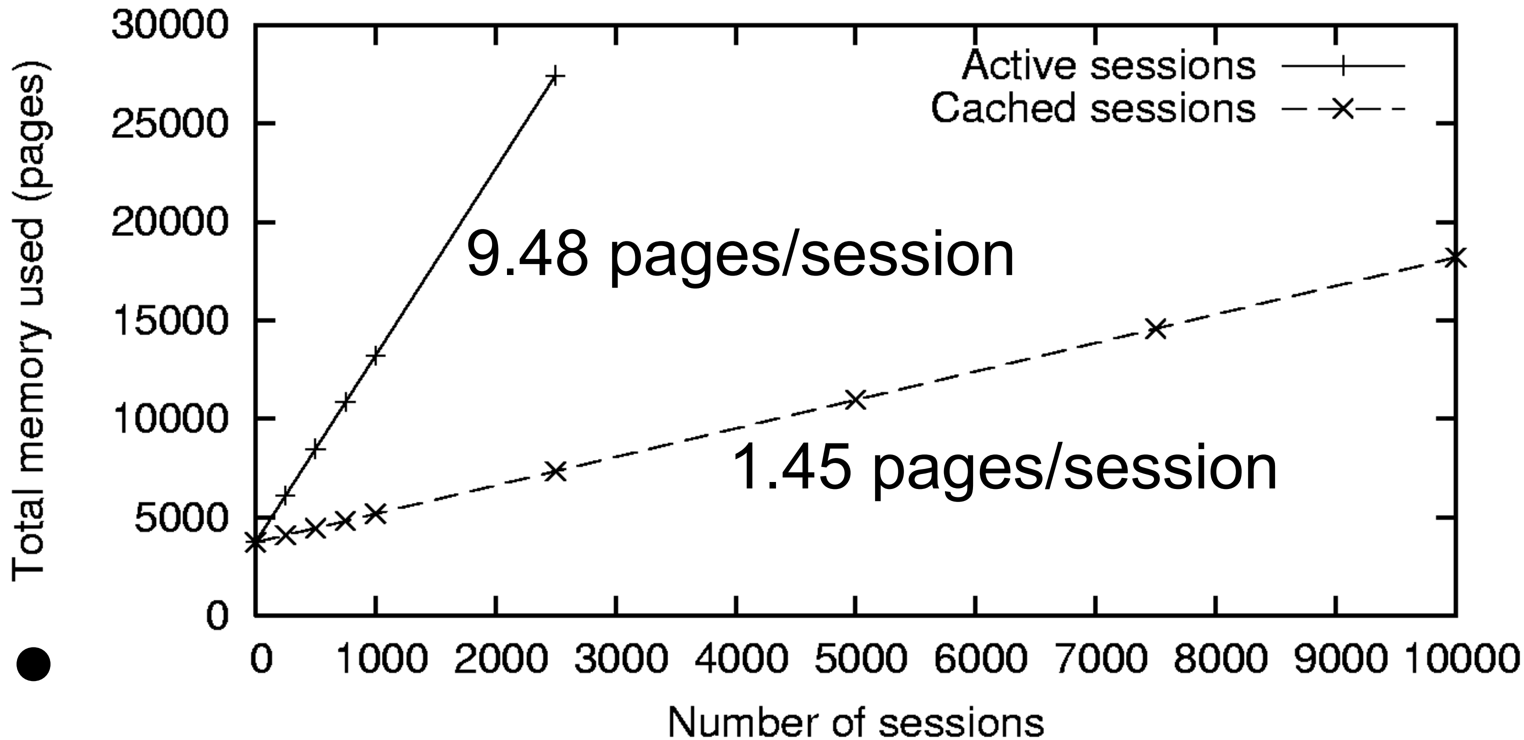
- How much memory do event processes use?
- Shopping cart application
  - Session state stored in event process
  - One event process per user



- Active session – Adding an item to the shopping cart
- Cache session – Deciding if you really want an item



Event Processes Conserve Memory

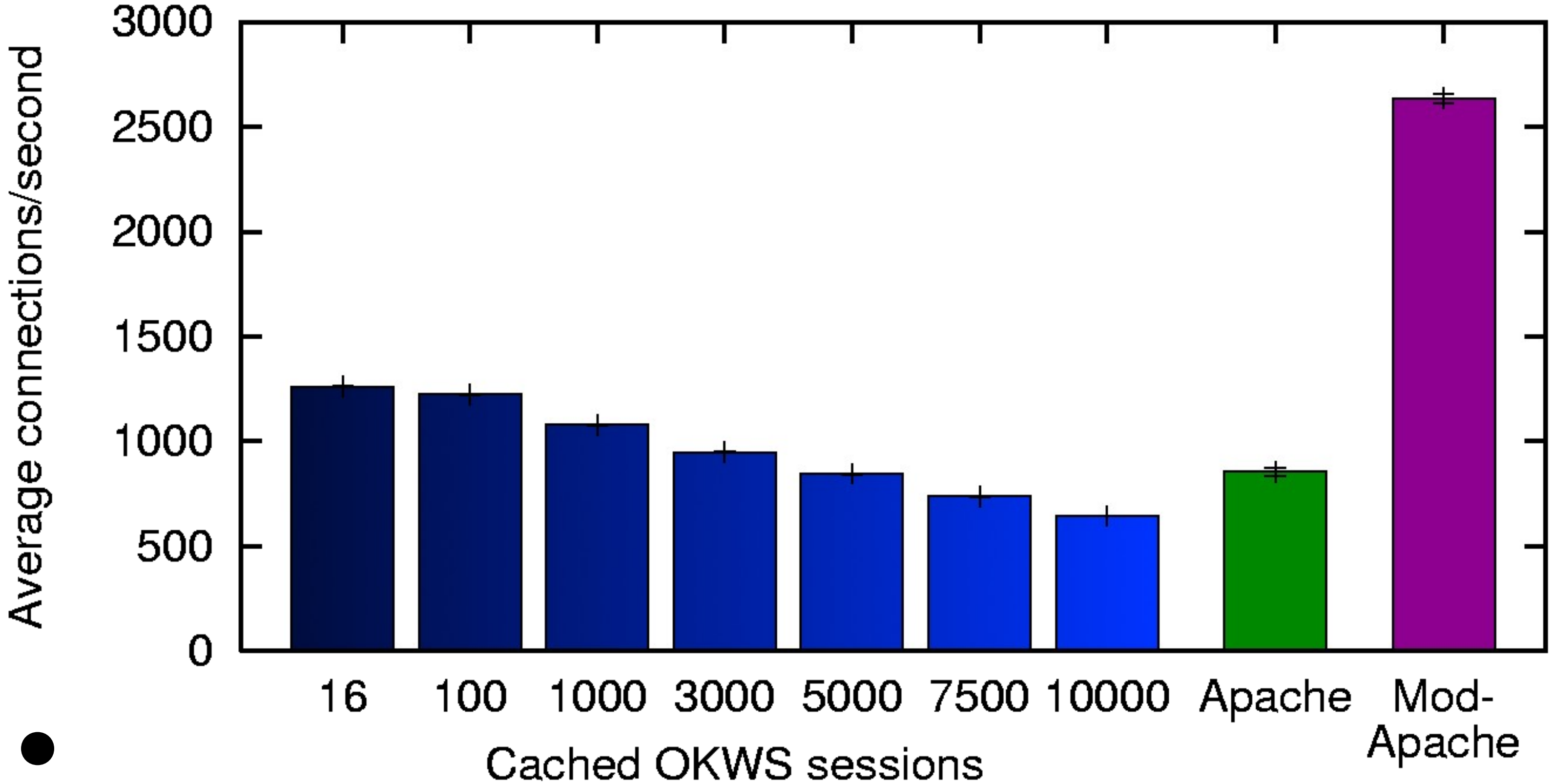


- Includes user and kernel memory
- Not too many active sessions on a large website

Experimental Setup – Throughput

- Simple character generation service
  - Not interested in application overhead
  - One event process per session (user)
- Compare to Apache & Mod-Apache
  - Varied concurrency to get best case performance
- Apache
  - Service runs as a CGI script
  - Connections are isolated into processes
  - Processes are not isolated or jailed on the system
- Mod-Apache
  - Service runs inside Apache process

Good Throughput



- For 16 sessions, 150% of Apache
- For 10,000 session, 75% of Apache

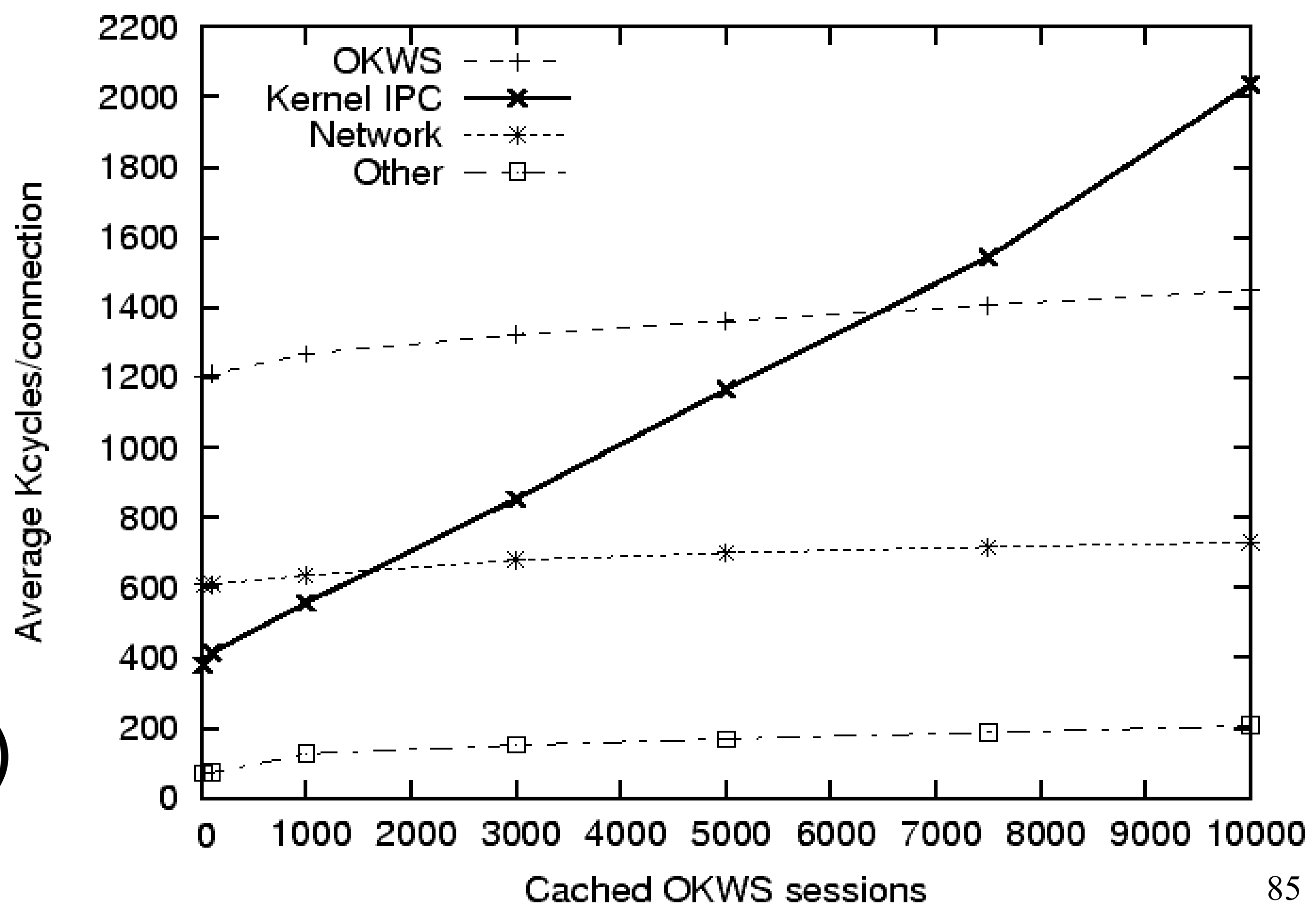
Latency

Server	Latency (μs) Median	90th Percentile
Mod-Apache	999	1,015
Apache	3,374	5,262
OKWS, 1 session	1,875	2,384
OKWS, 1000 sessions	3,414	6,767

Figure 8: The median and 90th percentile latencies of requests to various server confi gurations.

Label Cost Linear in Label Size

- Label cost starts small but outstrips OKWS cost around 6500 sessions
- Declassifiers label size O(#sessions)



Conclusion

- Asbestos labels make MAC more practical
  - Labels provide decentralized compartment creation & privilege
  - Event processes avoid accumulation of contamination
- The OK web server on Asbestos
  - Performs comparably to Apache
  - Provides better security properties than Apache