Automatic Placement of Authorization Hooks in the Linux Security Modules Framework

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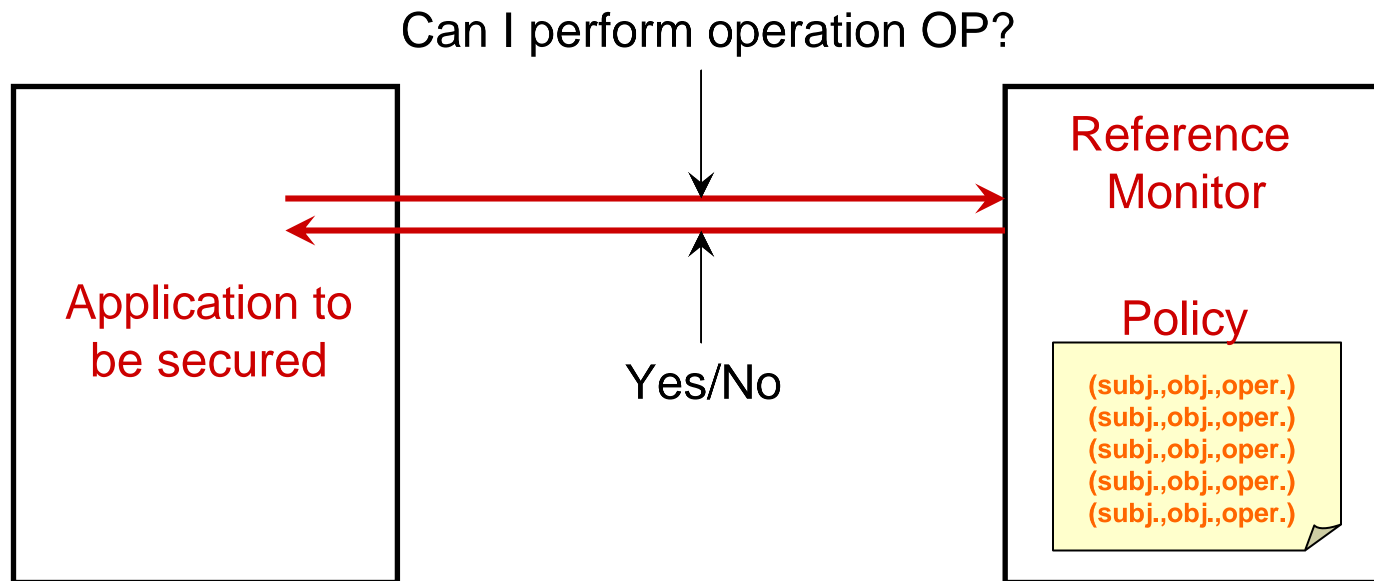
Context of this talk

- Authorization policies and their enforcement
- Three concepts:
  - *Subjects* (e.g., users, processes)
  - *Objects* (e.g., system resources)
  - Security-sensitive *operations* on objects.
- Authorization policy:
  - A set of triples: (Subject, Object, Operation)
- Key question: How to ensure that the authorization policy is enforced?

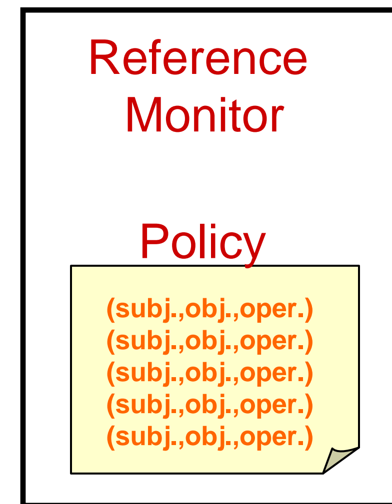
Enforcing authorization policies

- Reference monitor consults the policy.
- Application queries monitor at appropriate locations.



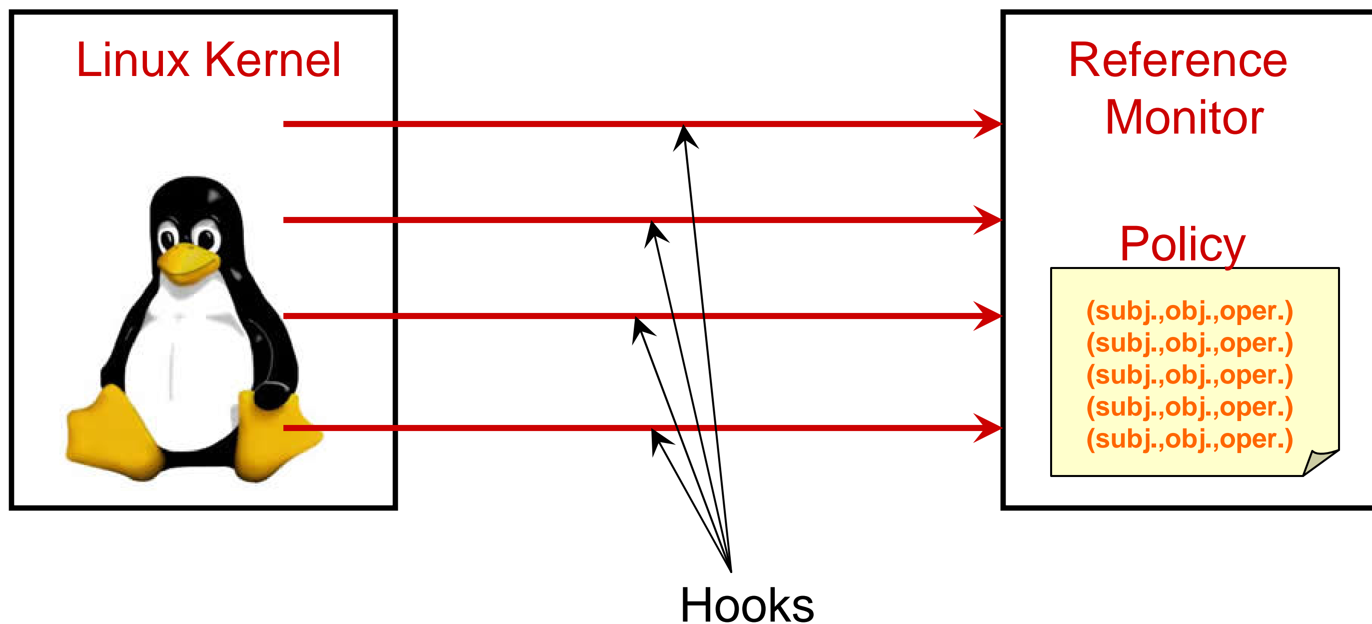
Linux security modules framework

- Framework for authorization policy enforcement.
- Uses a reference monitor-based architecture.
- Integrated into Linux-2.6



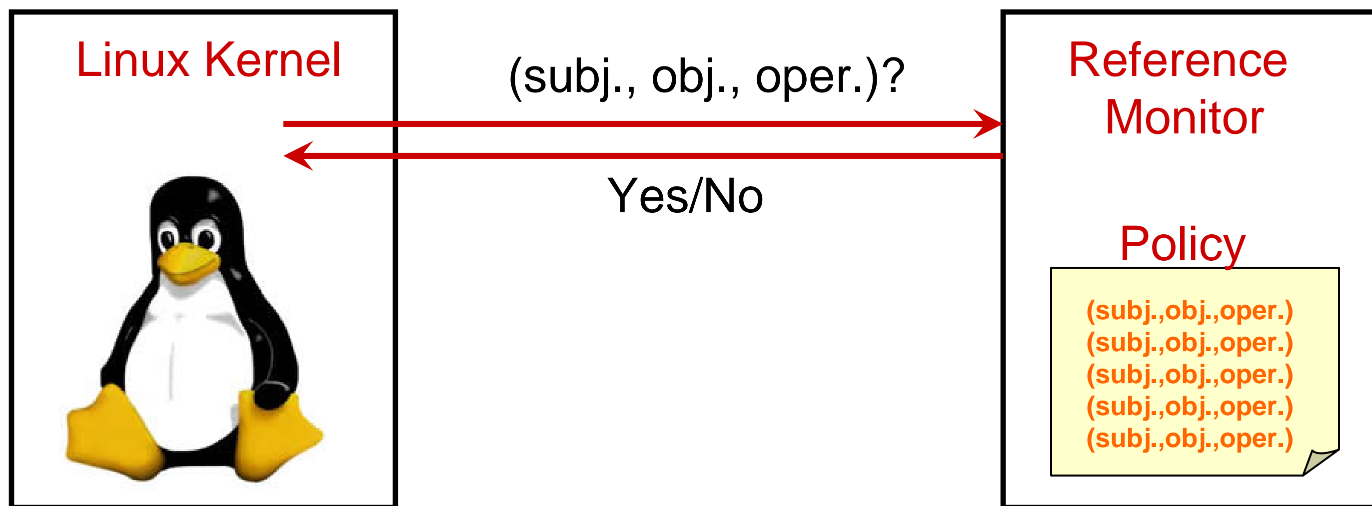
Linux security modules framework

- Reference monitor calls (*hooks*) placed appropriately in the Linux kernel.
- Each hook is an authorization query.



Linux security modules framework

- Authorization query of the form: (subj., obj., oper.)?
- Kernel performs operation only if query succeeds.



Virtual File System Code for Directory Removal

```
int vfs_rmdir(inode *dir, dentry *dentry) {
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    err = security_inode_rmdir(dir,dentry);
    if (!err) {
        dir->i_op->rmdir(dir,dentry);
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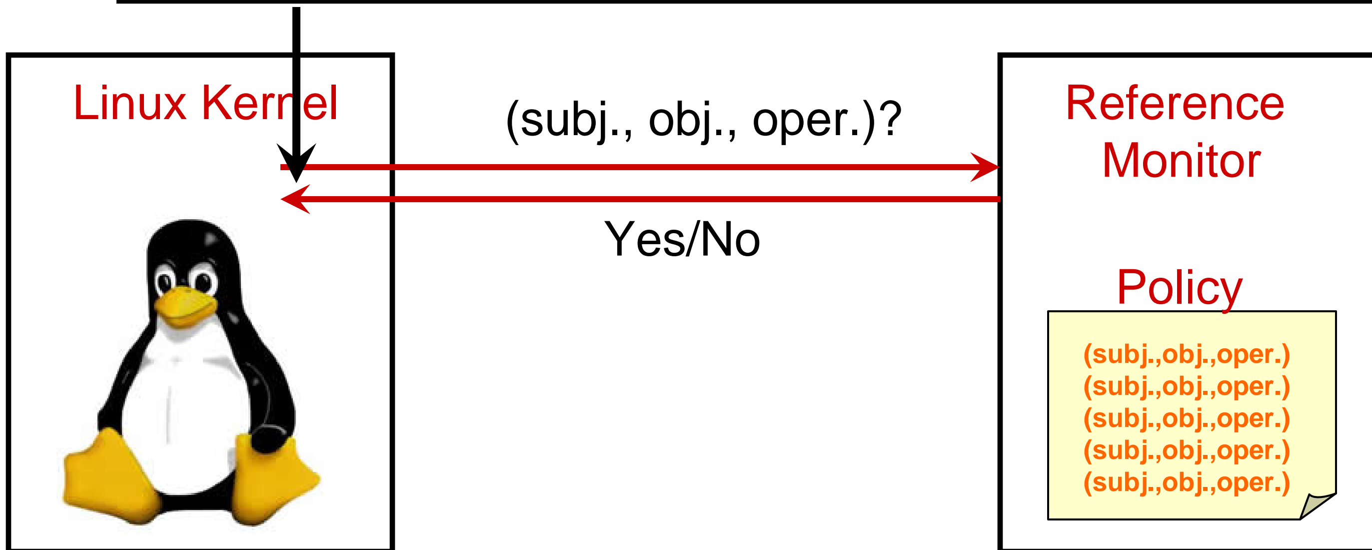

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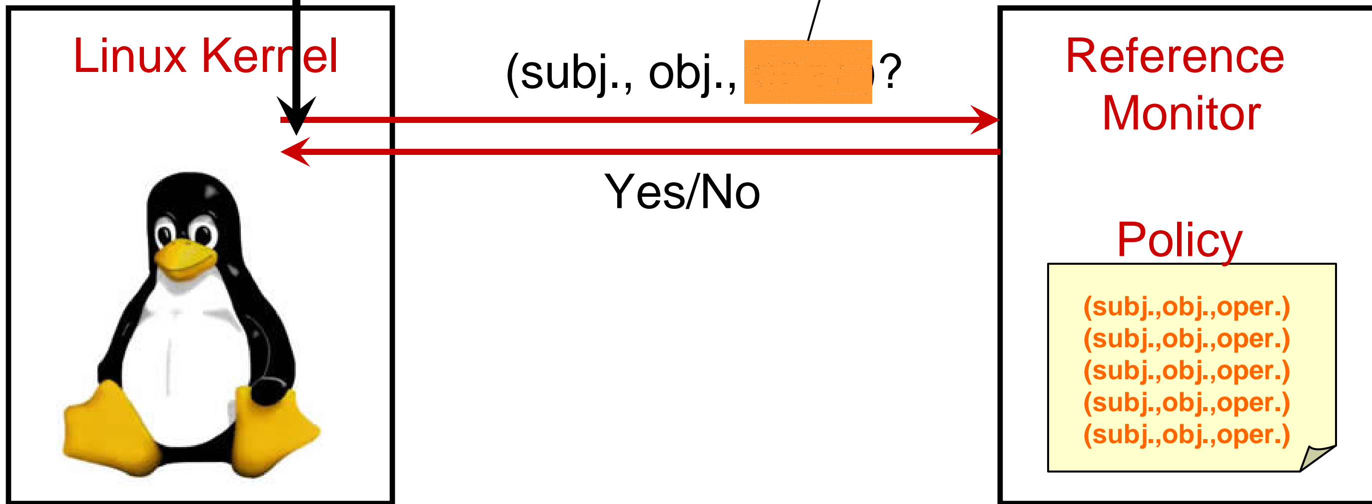

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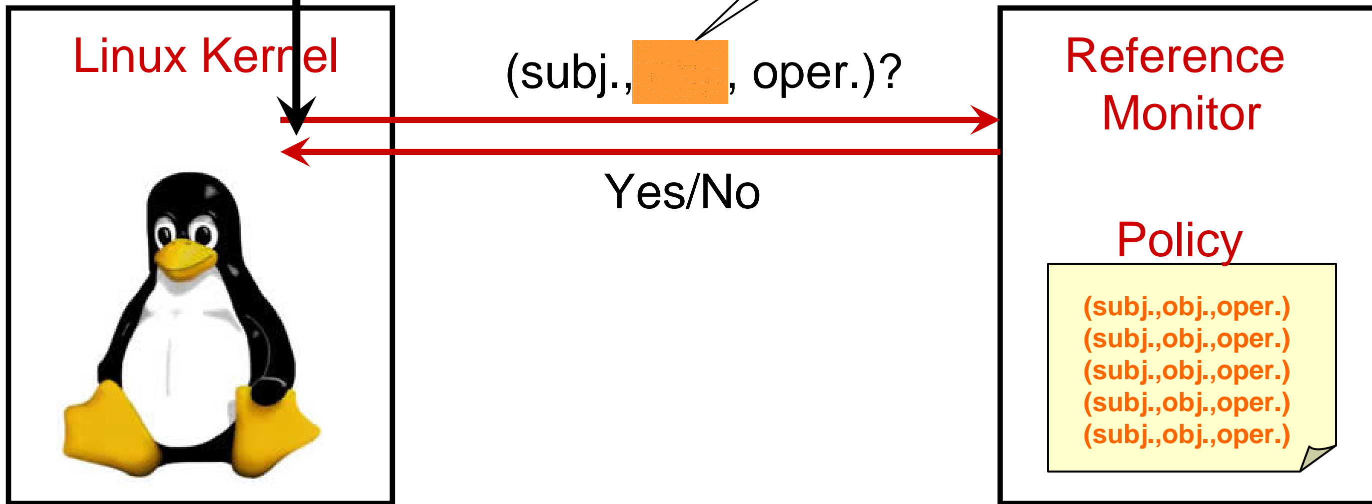

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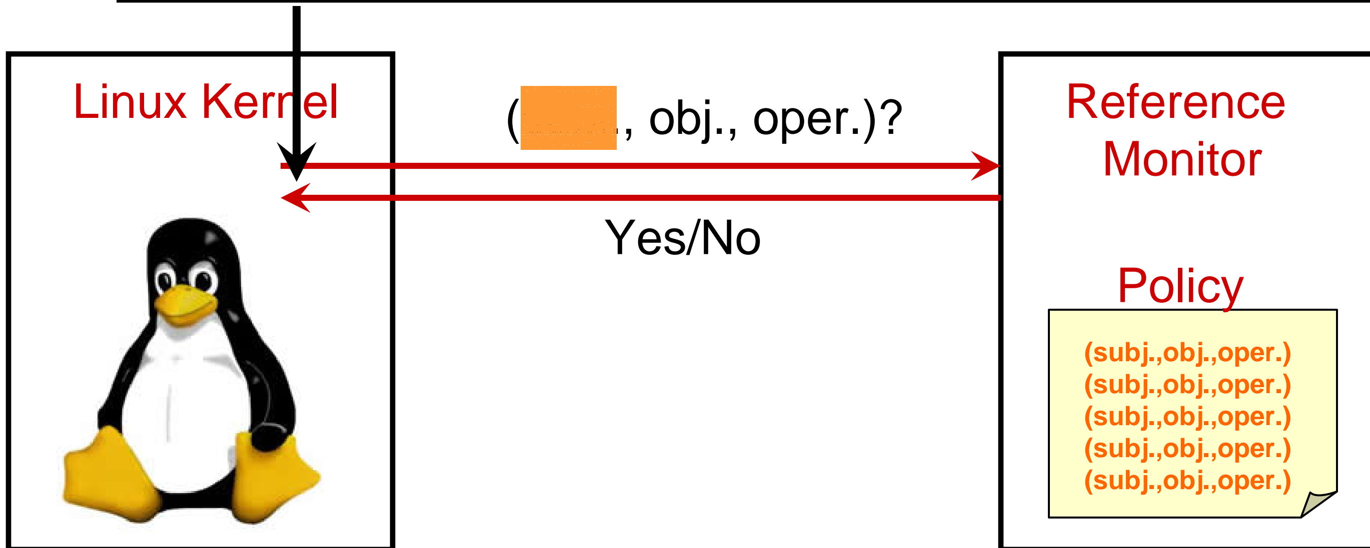

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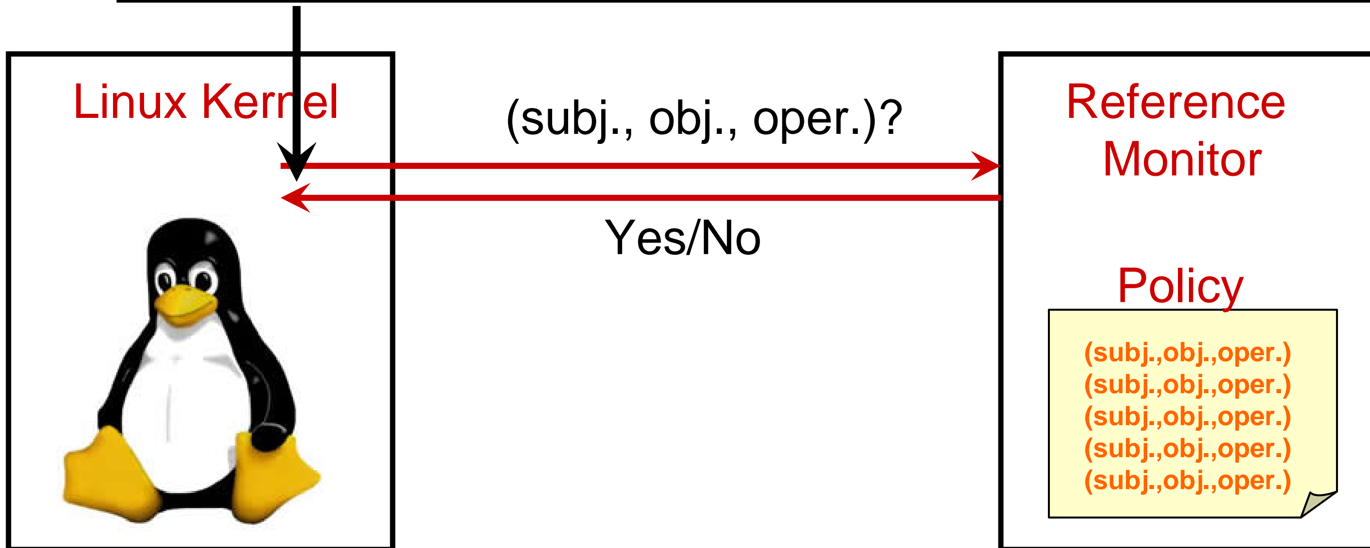

Key: Hooks must achieve *complete mediation.*

Hook placement is crucial

- Must achieve complete mediation.
  - Security-sensitive operations must be mediated by a hook that authorizes the operation.
- Current practice:
  - Hooks placed manually in the kernel.
  - Takes a long time: approx. 2 years for Linux security modules framework.
- Can this achieve complete mediation?
  - Prior work has found bugs in hook placement.
    [Zhang *et al.,* USENIX Security 2002, Jaeger *et al.,* ACM CCS 2002]

Main message of this talk

Static analysis can largely automate authorization hook placement and achieve complete mediation

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Reduces turnaround time of Linux Security Modules-like projects

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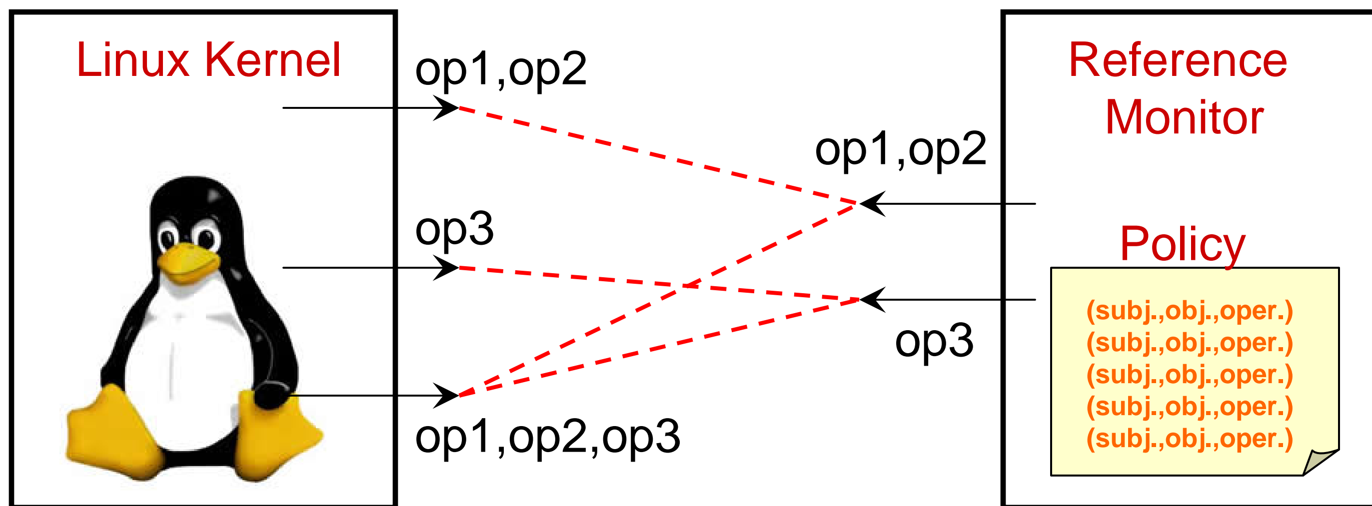
Static analysis can largely automate authorization hook placement and achieve <u>complete mediation</u>

Towards correctness by construction

Key intuition: Matchmaking

- Each kernel function performs an operation.
- Each hook authorizes an operation.
- Match kernel functions with appropriate hooks.

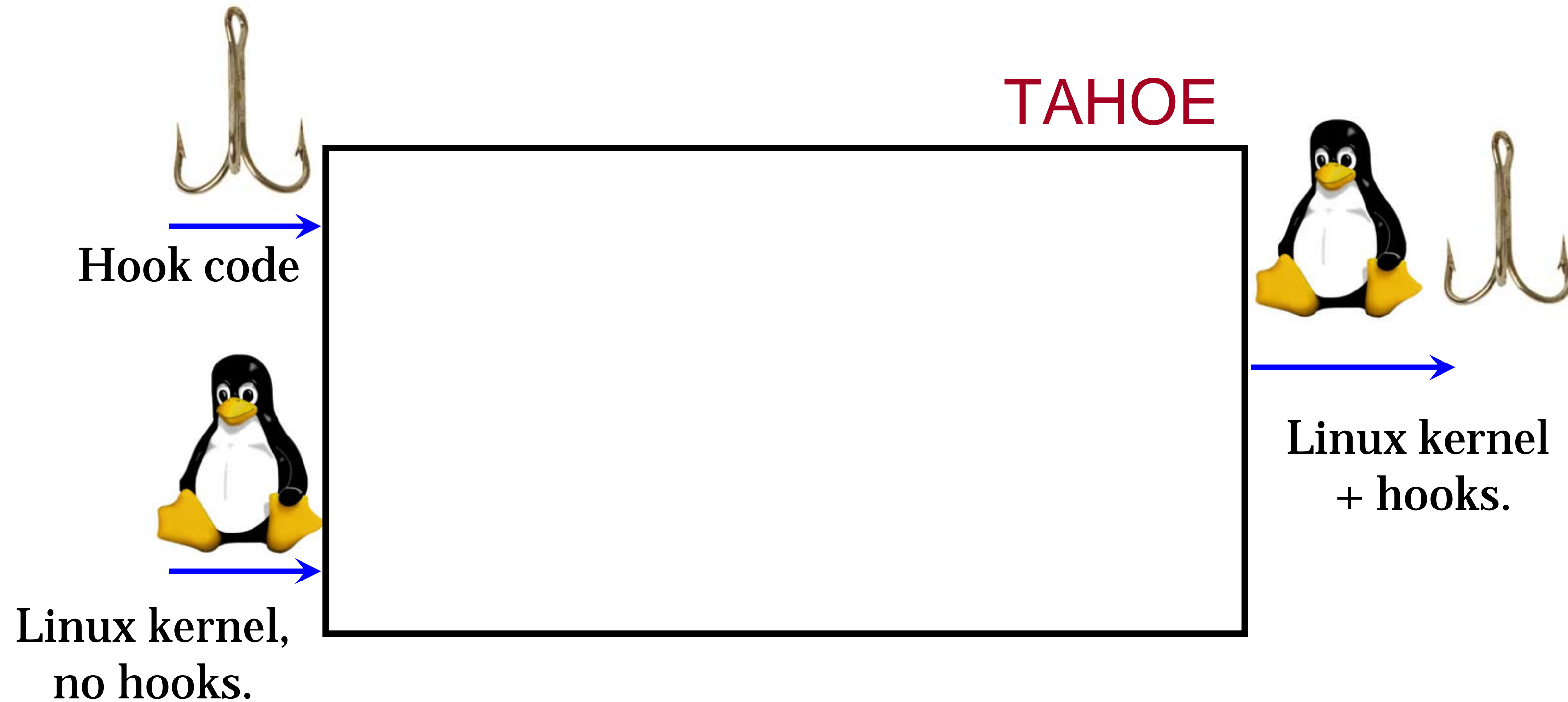


Tool for Authorization Hook Placement

- Input:
  - A set of security-sensitive operations.
  - Source code of reference monitor hooks.
  - Source code of the Linux kernel, without hooks placed.

- Output:
  - Linux kernel with hooks placed.

Tool for Authorization Hook Placement



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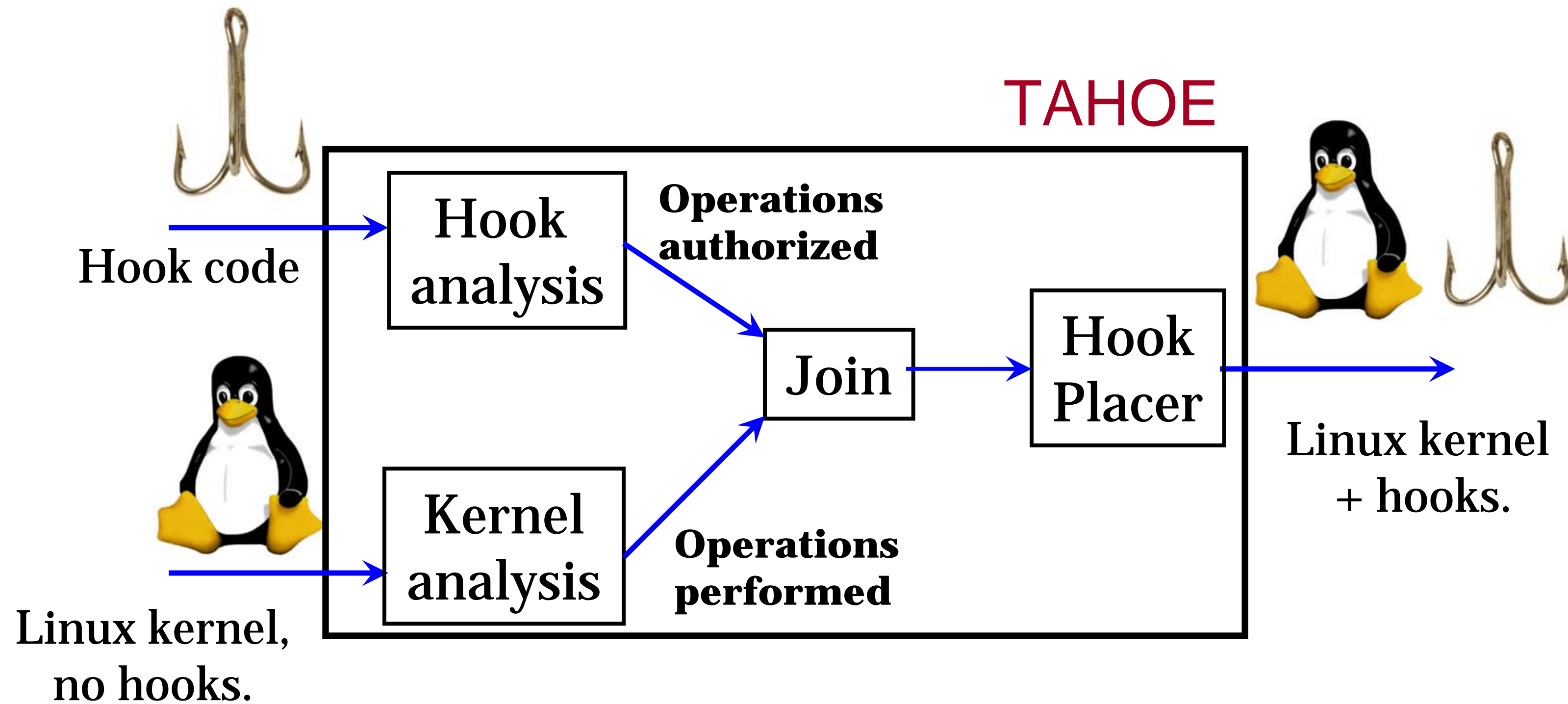
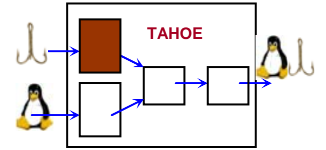


Security-sensitive operations

- We use the set of operations from the LSM implementation of SELinux.
- Comprehensive set of operations on resources:
  - **`FILE_READ`**
  - **`DIR_READ`**
  - **`FILE_WRITE`**
  - **`DIR_WRITE`**
  - **`SOCKET_RECV_MESG`**
  - **`SOCKET_LISTEN`**
  - … (504 such operations)

Authorization hook analysis



- Analyze source code of hooks and:
  - Recover the operations authorized.
  - Conditions under which they are authorized.

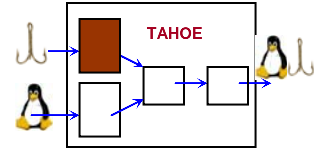
- Example:

```
int selinux_inode_permission(struct *inode, int mask) {
    op = 0;
    // s = info about process requesting operation

    if (mask & MAY_EXEC) op |= DIR_SEARCH;
    if (mask & MAY_WRITE) op |= DIR_WRITE;
    if (mask & MAY_READ) op |= DIR_READ;

    Query_Policy(s, inode, op);
}
```

Authorization hook analysis

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    op = 0;
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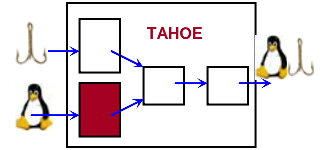
    if (mask & MAY_EXEC) op |= DIR_SEARCH;
    if (mask & MAY_WRITE) op |= DIR_WRITE;
    if (mask & MAY_READ) op |= DIR_READ;

    Query_Policy(s, inode, op);
}
```

- Flow-and-context-sensitive static analysis:
  - **DIR_READ** authorized if `**mask & MAY_READ**'
  - **DIR_WRITE** authorized if `**mask & MAY_WRITE**'
  - **DIR_SEARCH** authorized if `**mask & MAY_EXEC**'

Linux kernel analysis



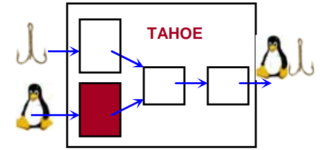
- Analyze Linux kernel to determine the security-sensitive operations performed by each function.
- More challenging than hook analysis.
- Example:

Virtual File System Code for Directory Removal

```
int vfs_rmdir (struct inode *dir, struct dentry *dentry) {
        ...
        dir->i_op->rmdir(dir, dentry);
        ...
}
```

Points to physical file system code

Example

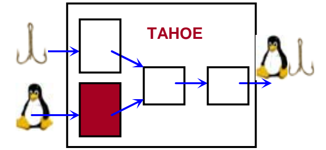


- How to infer the security-sensitive operations performed by `dir->i_op->rmdir(dir,dentry)`?

```
int vfs_rmdir (struct inode *dir, struct dentry *dentry) {
        ...
        dir->i_op->rmdir(dir, dentry);
        ...
}
```

```
$ ls foo/
bar/
```

Example



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```
int vfs_rmdir (struct inode *dir, struct dentry *dentry) {
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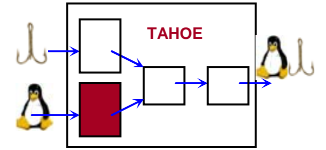
}
```

```
$ cd foo/
$ rmdir bar/
```

Example



- How to infer the security-sensitive operations performed by `dir->i_op->rmdir(dir,dentry)`?

```
int vfs_rmdir (struct inode *dir, struct dentry *dentry) {
      ...
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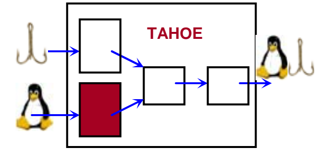
      ...
}
```

- Removing ba
  - Lookup of entry for o.
  - Removing (and henc ing to) `foo`'s data structures.

How to extract this information?

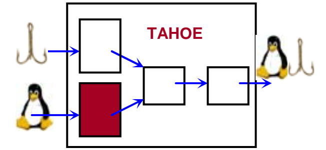
- `rmdir` involves `DIR_SEARCH`, `DIR_RMDIR` and `DIR_WRITE`.

Key observation



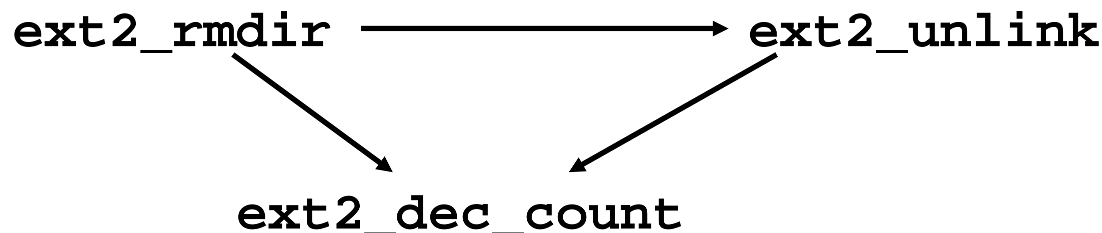
- Each security sensitive operation typically involves certain *idiomatic events*.
- Examples:
  - `DIR_WRITE :-` *Set* `inode->i_ctime &` *Call* `address_space_ops->prepare_write()`
  - `DIR_SEARCH :-` *Read* `inode->i_mapping`
  - `DIR_RMDIR :-` *Set* `inode->i_size TO 0 &` *Decrement* `inode->i_nlink`
- These rules are called *Idioms:*
  - Boolean combination of code-patterns.
  - Idiom language resembles Datalog.

Linux kernel analysis

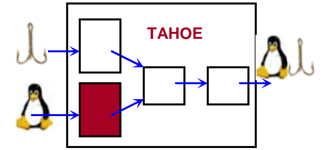


- *Flow-insensitive*, inter-procedural search for code patterns.
- Example: Call-graph of **`ext2`** file system

```
ext2_rmdir (struct inode *dir, struct dentry *dentry)
{
        ext2_unlink(…);
        …
        ext2_dec_count(…);
}
```



Linux kernel analysis



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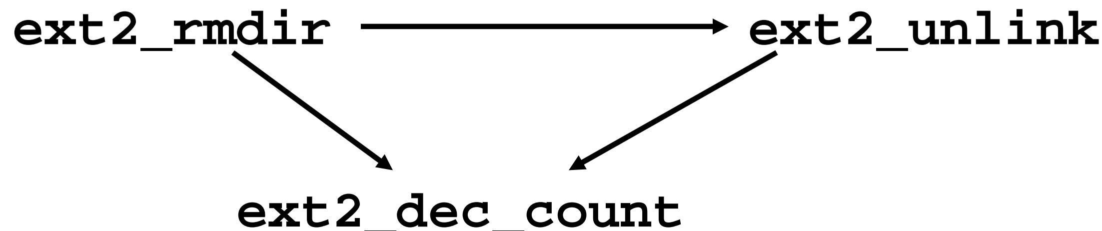

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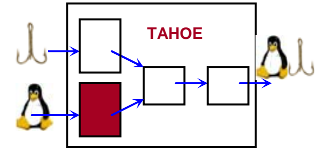

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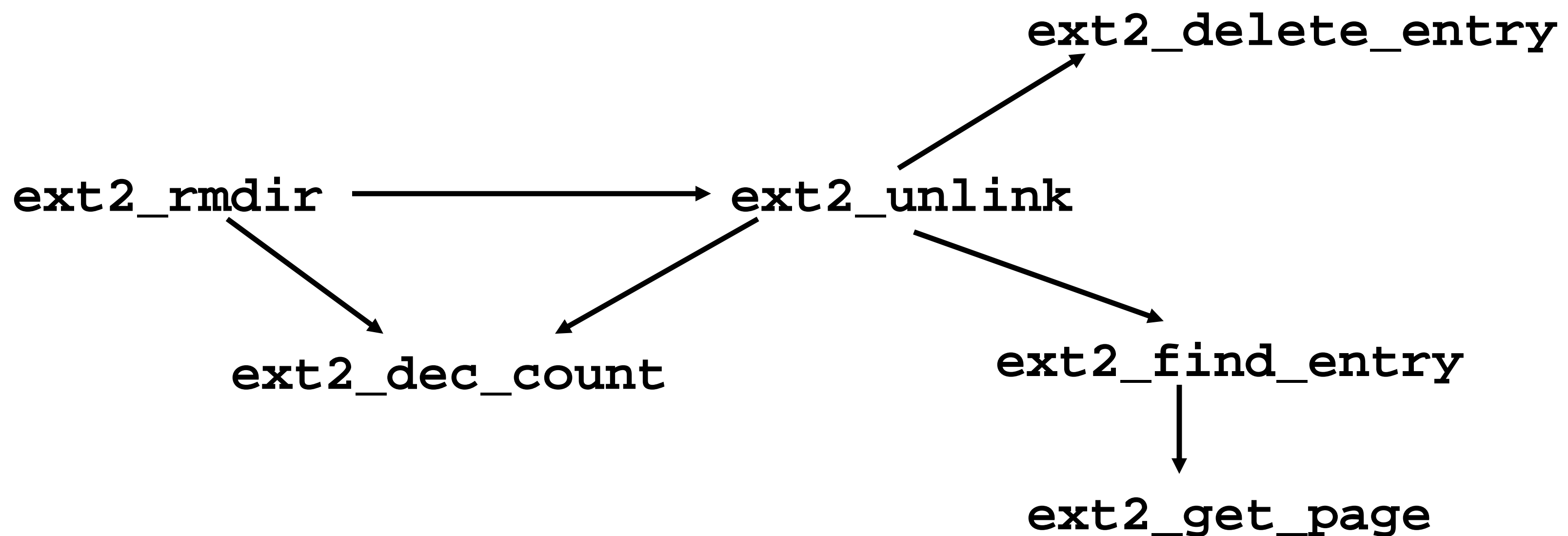

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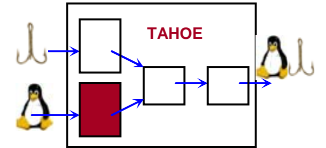
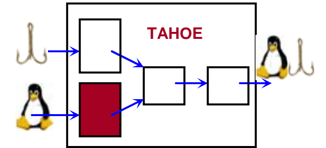


- *Flow-insensitive*, inter-procedural search for code patterns.
- Example: Call-graph of **`ext2`** file system

```
page->mapping->a_ops->prepare_write()
ext2_delete_entry
inode->i_size = 0
ext2_rmdir
ext2_unlink
ext2_dec_count
inode->i_nlink--
ext2_find_entry
ext2_get_page
mapping = inode->i_mapping
```

Linux kernel analysis



- `DIR_RMDIR :-` *Set* `inode->i_size` to 0 & *Decrement* `inode->i_nlink`
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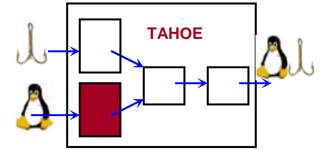
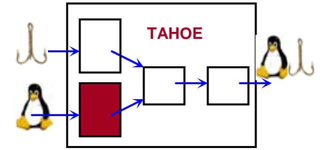
```

Result with ext2_rmdir



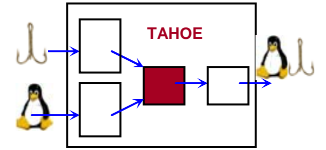
- *Flow-insensitive*, inter-procedural search for code patterns.
- Results:

Idioms

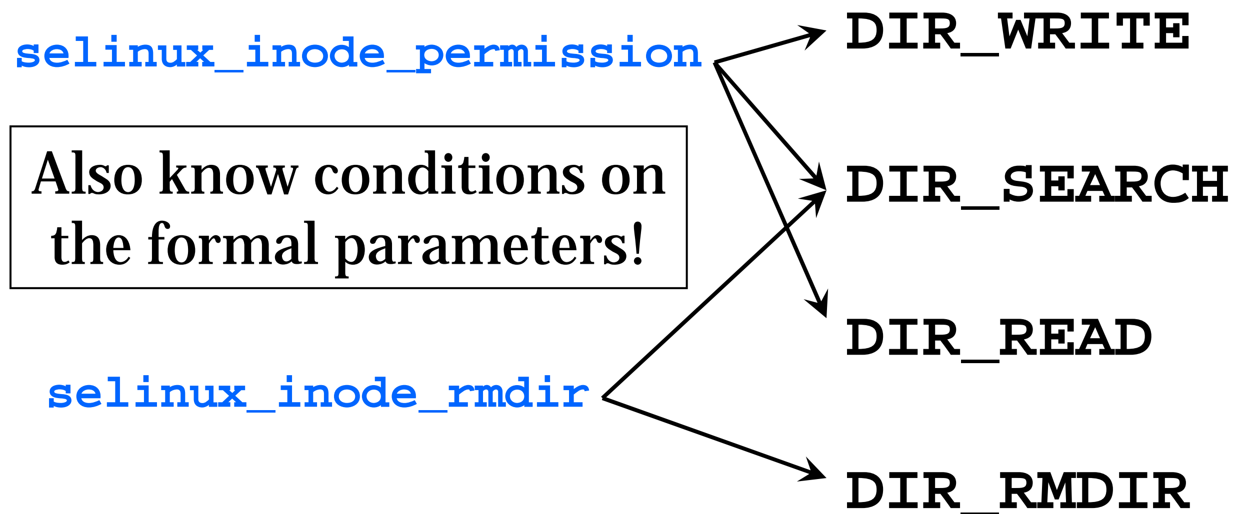


- Currently specified manually by us:
  - We wrote 150 idioms in a week.
  - We expect that a kernel developer can write these faster and more precisely.
- Difference from manual hook placement:
  - Only knowledge of kernel required.
  - One-time activity for the kernel: can reuse results for different reference monitors.
- Current work: Automating idiom writing.

Combining results



- From authorization hook analysis



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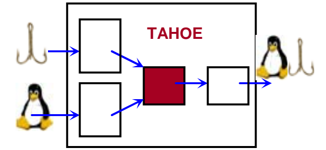
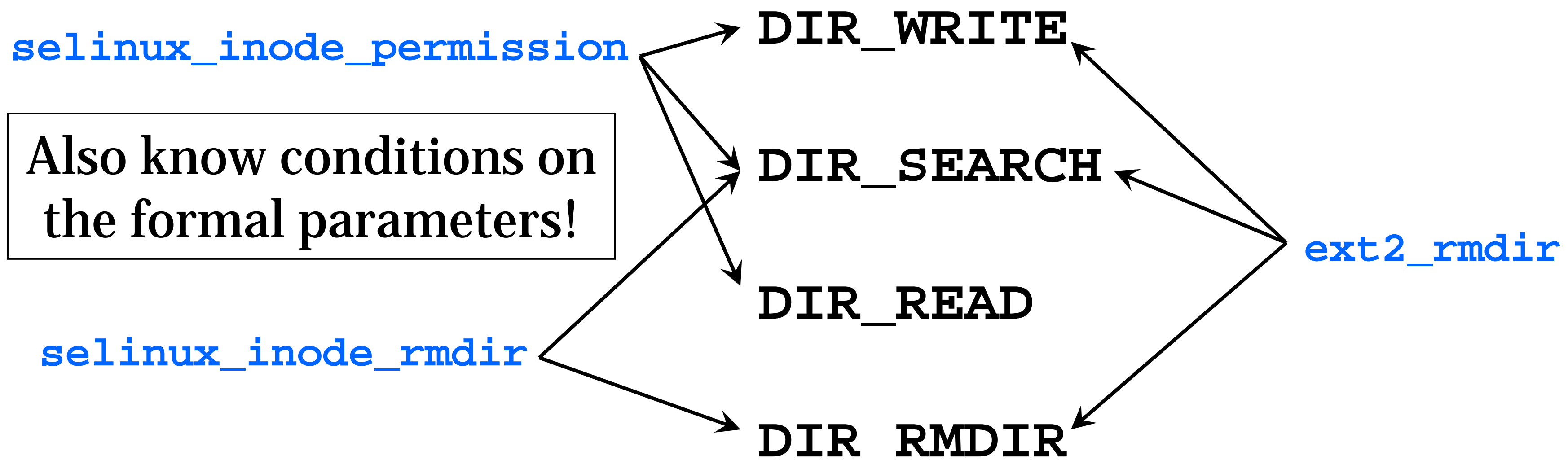
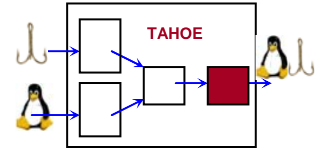


- From kernel analysis



Protect **ext2_rmdir** with
- **selinux_inode_rmdir**
- **selinux_inode_permission**(**MAY_WRITE**)

Placing hooks



- Naïve (but correct) approach:
  - Place hooks at each function call in the kernel using join analysis results.
  - May lead to redundant checks.

- TAHOE works differently:
  - Identifies a small set of *controlled functions*.
  - Suffices to place hooks to protect these.

- See paper for details.

Results

- Wrote idioms for `inode` and `socket` operations
- Tested with SELinux reference monitor and Linux kernel version 2.4.21

Hook type	Num.	Num. Locs	False pos.	False neg.
`inode`	26	40	13	4
`socket`	12	12	4	0

- False positives and negatives mainly because of imprecision in idioms.

Future work

- Hook placement for general-purpose servers
  - Example: X server.
  - Must enforce authorization policies on X clients.
  - Example: Prevent a "cut-and-paste" from a high-security `xterm` to a low-security `xterm`.
- Hundreds of such servers: database servers, web servers,…
- Manual hook placement?
  - *Simply infeasible*!

Summary of important ideas

- Can largely automate authorization hook placement using static analysis.
- Key idea: Matchmaking based on security-sensitive operations.
- TAHOE: A tool for LSM-hook placement.

Thank You

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