ECS 235B Module 53
Detecting Covert Channels

Detection

- Manner in which resource is shared controls who can send, receive using that resource
  - Noninterference
  - Shared Resource Matrix Methodology
  - Information flow analysis
  - Covert flow trees

Noninterference

- View “read”, “write” as instances of information transfer
- Then two processes can communicate if information can be transferred between them, even in the absence of a direct communication path
  - A covert channel
  - Also sounds like interference …

Example: SAT

- Secure Ada Target, multilevel security policy
- Approach:
  - $\pi(i, l)$ removes all instructions issued by subjects dominated by level l from instruction stream i
  - $A(i, \sigma)$ state resulting from execution of i on state σ
  - $\sigma.v(s)$ describes subject s's view of state σ
- System is noninterference-secure iff for all instruction sequences i, subjects s with security level $l(s)$, states σ,

$$A(\pi(i, l(s)), \sigma).v(s) = A(i, \sigma).v(s)$$

Theorem

- Version of the Unwinding Theorem
- Let Σ be set of system states. A specification is noninterference-secure if, for each subject *s* at security level *l*(*s*), there exists an equivalence relation $\equiv : \Sigma \times \Sigma$ such that
  - for $\sigma_1, \sigma_2 \in \Sigma$, when $\sigma_1 \equiv \sigma_2$, $\sigma_1.v(s) = \sigma_2.v(s)$
  - for $\sigma_1, \sigma_2 \in \Sigma$ and any instruction *i*, when $\sigma_1 \equiv \sigma_2$, $A(i, \sigma_1) \equiv A(i, \sigma_2)$
  - for $\sigma \in \Sigma$ and instruction stream *i*, if $\pi(i, l(s))$ is empty, $A(\pi(i, l(s)), \sigma).v(s) = \sigma.v(s)$

Intuition

- System is noninterference-secure if:
  - Equivalent states have the same view for each subject
  - View remains unchanged if any instruction is executed
  - Instructions from higher-level subjects do not affect the state from the viewpoint of the lower-level subjects

Analysis of SAT

- Focus on object creation instruction and readable object set
- In these specifications:
  - s subject with security level $l(s)$
  - o object with security level $l(o)$, type $\tau(o)$
  - σ current state
  - Set of existing objects listed in a global object table $T(\sigma)$

Specification 1

- *object_create*:

$$[\ \sigma' = \textit{object\_create}(s,o,l(o),\tau(o),\sigma) \wedge \sigma' \neq \sigma\ ]$$
$$\Leftrightarrow$$
$$[\ o \notin T(\sigma) \wedge l(s) \leq l(o)\ ]$$

- The create succeeds if, and only if, the object does not yet exist and the clearance of the object will dominate the clearance of its creator
  - In accord with the "writes up okay" idea

Specification 2

- readable object set: set of existing objects that subject could read
  - *can_read*(s, o, σ) true if in state σ, o is of a type that s can read (ignoring permissions)
- $o \notin readable(s, \sigma) \Leftrightarrow [\, o \notin T(\sigma) \vee \neg(l(o) \leq l(s)) \vee \neg(can\_read(s, o, \sigma))]$
- Can't read a nonexistent object, one with a security level that the subject's security level does not dominate, or object of the wrong type

Specification 3

- SAT enforces tranquility
  - Adding object to readable set means creating new object
- Add to readable set:

$$[o \notin \mathit{readable}(s, \sigma) \land o \in \mathit{readable}(s, \sigma')] \Leftrightarrow$$
$$[\sigma' = \mathit{object\_create}(s,o,l(o),\tau(o),\sigma) \land o \notin T(\sigma) \land l(s') \leq l(o) \leq l(s) \land$$
$$\mathit{can\_read}(s, o, \sigma')]$$

- Says object must be created, levels and discretionary access controls set properly

Check for Covert Channels

- σ_1, σ_2 the same except:
  - *o* exists only in latter
  - $\neg(l(o) \leq l(s))$
- Specification 2:
  - $o \notin readable(s, \sigma_1)$ { *o* doesn't exist in σ_1}
  - $o \notin readable(s, \sigma_2)$ { $\neg(l(o) \leq l(s))$ }
- Thus $\sigma_1 \equiv \sigma_2$
  - Condition 1 of theorem holds

Continue Analysis

- s' issues command to create o:
  - with $l(o) = l(s)$; and
  - of type with $can\_read(s, o, \sigma_1')$
    - σ_1' state after $object\_create(s', o, l(o), \tau(o), \sigma_1)$
- Specification 1
  - σ_1' differs from σ_1 with o in $T(\sigma_1)$
- New entry satisfies:
  - $can\_read(s, o, \sigma_1')$
  - $l(s') \le l(o) \le l(s)$, where s' created o

Continue Analysis

- o exists in σ_2 so:

$$\sigma_2' = object\_create(s', o, \sigma_2) = \sigma_2$$

- But this means

$$\neg[\ A(object\_create(s', o, l(o), \tau(o), \sigma_2), \sigma_2) \equiv A(object\_create(s', o, l(o), \tau(o), \sigma_1), \sigma_1)\ ]$$

  - Because create fails in σ_2 but succeeds in σ_1
- So condition 2 of theorem fails
- This implies a covert channel as system is not noninterference-secure

Example Exploit

- To send 1:
  - High subject creates high object
  - Recipient tries to create same object but at low
    - Creation fails, but no indication given
  - Recipient gives different subject type permission to read, write object
    - Again fails, but no indication given
  - Subject writes 1 to object, reads it
    - Read returns nothing

Example Exploit

- To send 0:
  - High subject creates nothing
  - Recipient tries to create same object but at low
    - Creation succeeds as object does not exist
  - Recipient gives different subject type permission to read, write object
    - Again succeeds
  - Subject writes 1 to object, reads it
    - Read returns 1

Use

- Can analyze covert storage channels
  - Noninterference techniques reason in terms of security levels (attributes of objects)
- Covert timing channels much harder
  - You would have to make ordering an attribute of the objects in some way

SRMM

- Shared Resource Matrix Methodology
- Goal: identify shared channels, how they are shared
- Steps:
  - Identify all shared resources, their visible attributes [rows]
  - Determine operations that reference (read), modify (write) resource [columns]
  - Contents of matrix show how operation accesses the resource

Example

- Multilevel security model
- File attributes:
  - existence, owner, label, size
- File manipulation operations:
  - *read*, *write*, *delete*, *create*
  - *create* succeeds if file does not exist; gets creator as owner, creator's label
  - others require file exists, appropriate labels
- Subjects:
  - High, Low

Shared Resource Matrix

	read	**write**	**delete**	**create**
existence	R	R	R, M	R, M
owner			R	M
label	R	R	R	M
size	R	M	M	M

Covert Storage Channel

- Properties that must hold for covert storage channel:
  1. Sending, receiving processes have access to same *attribute* of shared object;
  2. Sender can modify that attribute;
  3. Receiver can reference that attribute; and
  4. Mechanism for starting processes, properly sequencing their accesses to resource

Example

- Consider attributes with both R, M in rows
- Let High be sender, Low receiver
- *create* operation both references, modifies existence attribute
  - Low can use this due to semantics of create
- Need to arrange for proper sequencing accesses to existence attribute of file (shared resource)

Use of Channel

- 3 files: *ready*, *done*, *1bit*
- Low creates *ready* at High level
- High checks that file exists
  - If so, to send 1, it creates *1bit*; to send 0, skip
  - Delete *ready*, create *done* at High level
- Low tries to create *done* at High level
  - On failure, High is done
  - Low tries to create *1bit* at level High
- Low deletes *done*, creates *ready* at High level

Covert Timing Channel

- Properties that must hold for covert timing channel:
  1. Sending, receiving processes have access to same *attribute* of shared object;
  2. Sender, receiver have access to a time reference (wall clock, timer, event ordering, …);
  3. Sender can control timing of detection of change to that attribute by receiver; and
  4. Mechanism for starting processes, properly sequencing their accesses to resource

Example

- Revisit variant of KVM/370 channel
  - Sender, receiver can access ordering of requests by disk arm scheduler (attribute)
  - Sender, receiver have access to the ordering of the requests (time reference)
  - High can control ordering of requests of Low process by issuing cylinder numbers to position arm appropriately (timing of detection of change)
  - So whether channel can be exploited depends on whether there is a mechanism to (1) start sender, receiver and (2) sequence requests as desired

Uses of SRM Methodology

- Applicable at many stages of software life cycle model
  - Flexbility is its strength
- Used to analyze Secure Ada Target
  - Participants manually constructed SRM from flow analysis of SAT model
  - Took transitive closure
  - Found 2 covert channels
    - One used assigned level attribute, another assigned type attribute

Summary

- Methodology comprehensive but incomplete
  - How to identify shared resources?
  - What operations access them and how?
- Incompleteness a benefit
  - Allows use at different stages of software engineering life cycle
- Incompleteness a problem
  - Makes use of methodology sensitive to particular stage of software development

Information Flow Analysis

- When exception occurs due to value of variable, information leaks about the value – a covert channel
  - Same for synchronization and IPC primitives, because one process controls when it sends message or blocks to receive one
  - Shared variables are *not* covert channel as they are intended to share values
- Method for identifying covert storage channels in source code
  - Assertion: these arise when processes can view, alter kernel variables
  - So identify these variables
    - May be directly referenced or indirectly referenced via system calls

Step 1

- Identify kernel functions, processes for analysis
  - Processes function at privileged level, but carry out actions for ordinary users
  - Ignore those executing on behalf of administrators (they can leak information directly)
  - Same with system calls available only to system administrator

Step 2

- Identify kernel variables user process can view and/or alter
  - Process must control *how* variable is altered
  - Process must be able to detect *that* variable was altered
- Detection criteria
  - Value of a variable is obtained from system call
  - Calling process can detect at least 2 different states of that variable
- Examples
  - If system call assigns fixed value to a particular variable, process cannot control how that variable is altered
  - If value of *x* causes an error, state of *x* can be determined from the error indicator

Directly vs. Indirectly Visible

x directly visible to caller as it is returned directly to caller

```
x := func(abc, def);
if x = 0 then
    x := x + 10;
return x;
```

y not directly visible to caller, but indirectly visible as its state observed through *z*

```
y := func(abc, def);
if y = 0 then
    z := 1;
else
    z := 0;
return z;
```

Step 3

- Analyze variables looking for covert channels
  - Use method similar to that of SRM
  - Discard primitives associated with variables that can *only* be altered or *only* be viewed
  - Assume recipient's clearance does not dominate sender's, and compare resulting primitives to model of access control

Covert Flow Trees

- Information flow through shared resources modeled using tree
  - Flow paths identified, and analyzed to see if each is legitimate
- 5 types of nodes
  - *Goal symbols*: states that must exist for information to flow
  - *Operation symbol*: symbol representing primitive operation
  - *Failure symbol*: information cannot be sent along the path containing it
  - *And symbol*: goal reached when these hold for all children
    - If the child is a goal, then the goal is reached; and
    - The child is an operation
  - *Or symbol*: goal reached when either of these hold for any children
    - If the child is a goal, then the goal is reached; or
    - The child is an operation

More on Goal Symbols

- *Modification goal*: reached when attribute is modified
- *Recognition goal*: reached when modification of attribute is detected
- *Direct recognition goal*: reached when subject can detect modification of attribute by direct reference or calling a function that returns it
- *Inferred recognition goal*: reached when subject can detect modification of attribute without directly referencing it or calling a function that references attribute directly
- *Inferred-via goal*: reached when information passed from one attribute to others using specified primitive operation
- *Recognized-new-state goal*: reached when an attribute that was modified when information passed using it is specified by inferred-via goal

Example Program

```
procedure Lockfile(f: file): boolean;               (* lock file if not locked; return *)
begin                                                (* false if locked, true otherwise *)
        if not f.locked and empty(f.inuse) then
                f.locked := true;
        Lockfile := not f.locked;
end;
procedure Unlockfile(f:  file);                      (* unlock file *)
begin
        if f.locked then
                f.locked :=  false;
end;
function Filelocked(f:  file):  boolean;             (* return state of file locking *)
begin
        Filelocked := f.locked;
end;
```

Example Program

```
procedure Openfile(f:  file);   (* open file if not locked and *)
begin                                   (* permissions allow it *)
        if not f.locked and read_access(process_id, f) then
                (* add the process ID to the inuse set *)
                f.inuse = f.inuse + process_id;
end;
function Fileopened(f:  file):  boolean;(* if permissions allow process to read file, *)
begin                                   (* say if open; else return random value.     *)
        if not read_access(process_id, f) then
                Fileopened := random(true, false);
        else
                Fileopened :=  not isempty(f.inuse);
end;
```

Step 1

- Determine attributes that primitive operations reference, modify, return

	Lockfile	**Unlockfile**	**Filelocked**	**Openfile**	**Fileopened**
reference	*locked,inuse*	*locked*	*locked*	*locked,inuse*	*inuse*
modify	*locked*	∅	∅	*inuse*	∅
return	∅	∅	*locked*	∅	*inuse*

Step 2

- Construct the flow tree; controlled by type of goal
- Construction ends when all paths terminate in either operation symbol of failure symbol
  - If loops occur, a parameter defines number of times path may be traversed

Step 2 (*con't*)

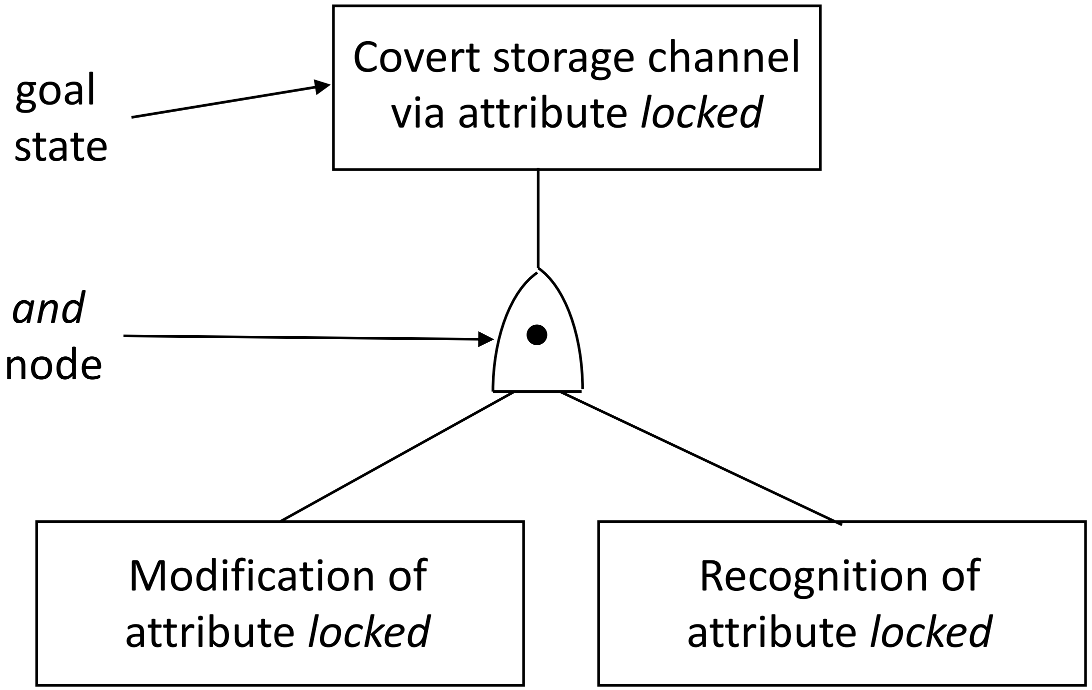
- Topmost goal: requires attribute be modified and the modification be recognized
  - 1 child (*and*) with 2 goals (modification, recognition goal symbols)
- Modification goal: requires primitive operation to modify attribute
  - 1 child (*or*) with 1 child operation symbol per operation for all operations that modify attribute
- Recognition goal: subject directly recognize or infer change in attribute
  - 1 child (*or*) with 2 children (direct recognition, inferred recognition goals)

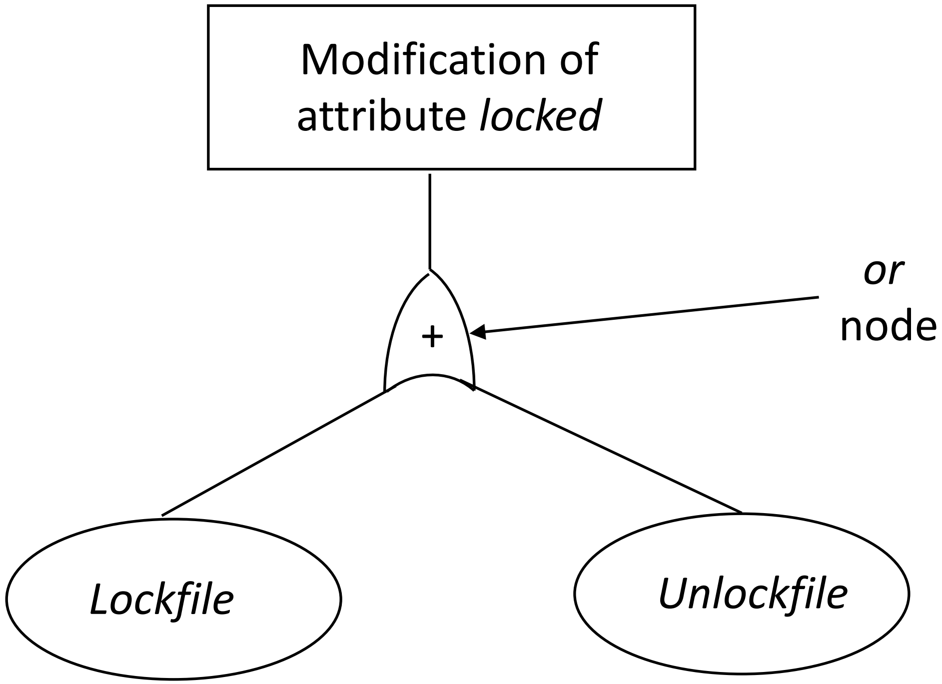
Step 2 (*con't*)

- Direct recognition goal: operation accesses attribute
  - 1 child (*or*) with 1 child operation symbol per operation for each operation that returns attribute
- Inferred recognition goal: modification referred on basis of 1 or more attributes
  - 1 child (*or*) with 1 child inferred-via symbol per operation for each operation that references an attribute and modifies an attribute
- Inferred-via goal: value of attribute inferred via some operation and new state of attribute recognized
  - 1 child (*and*) with 2 children (operation, recognize-new-state goal symbols)
- Recognize-new-state goal: value of attribute inferred via some operation and new state of attribute recognized, requiring a recognition goal for attribute
  - 1 child (*or*) and for each attribute enabling inference of modification of attribute in question, 1 child (recognition goal symbol)

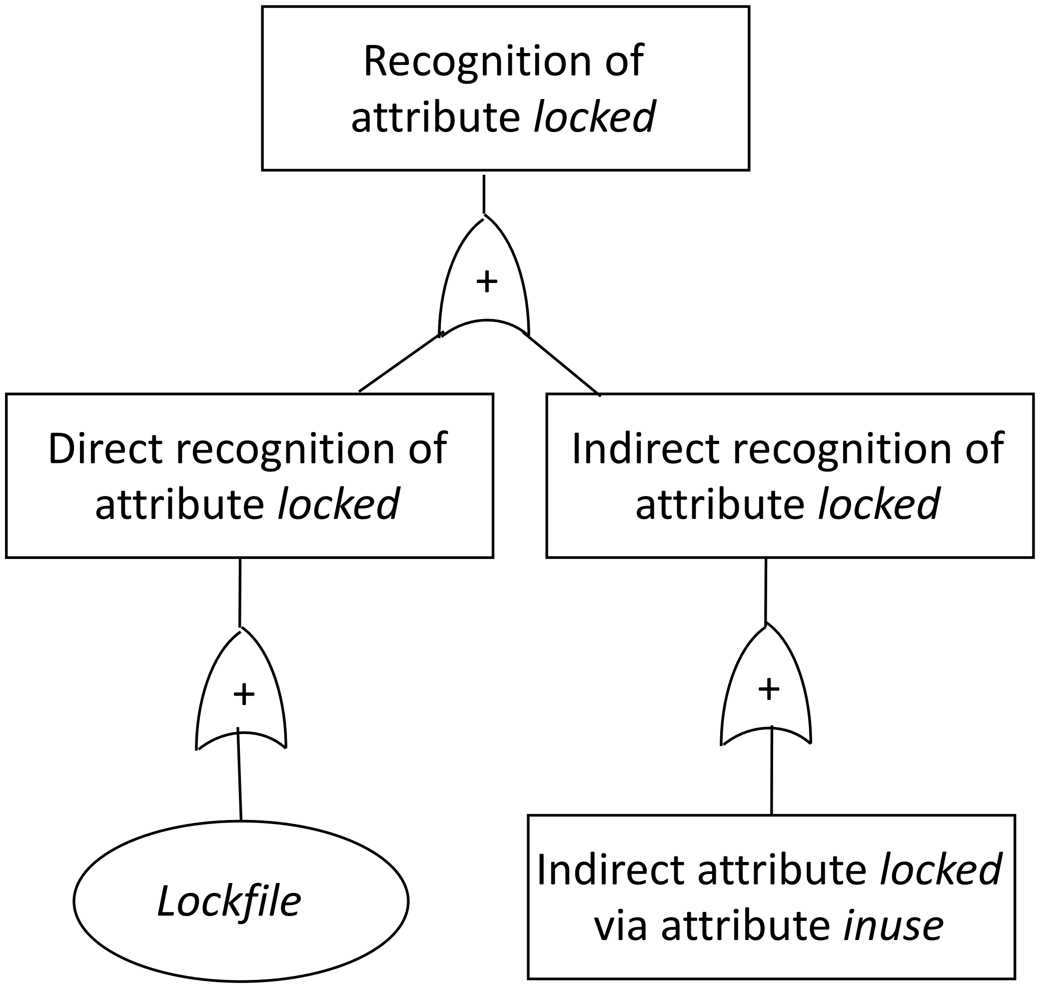
Example: Goal State and Modification Branch

- The next few slides build covert flow tree for attribute *locked*

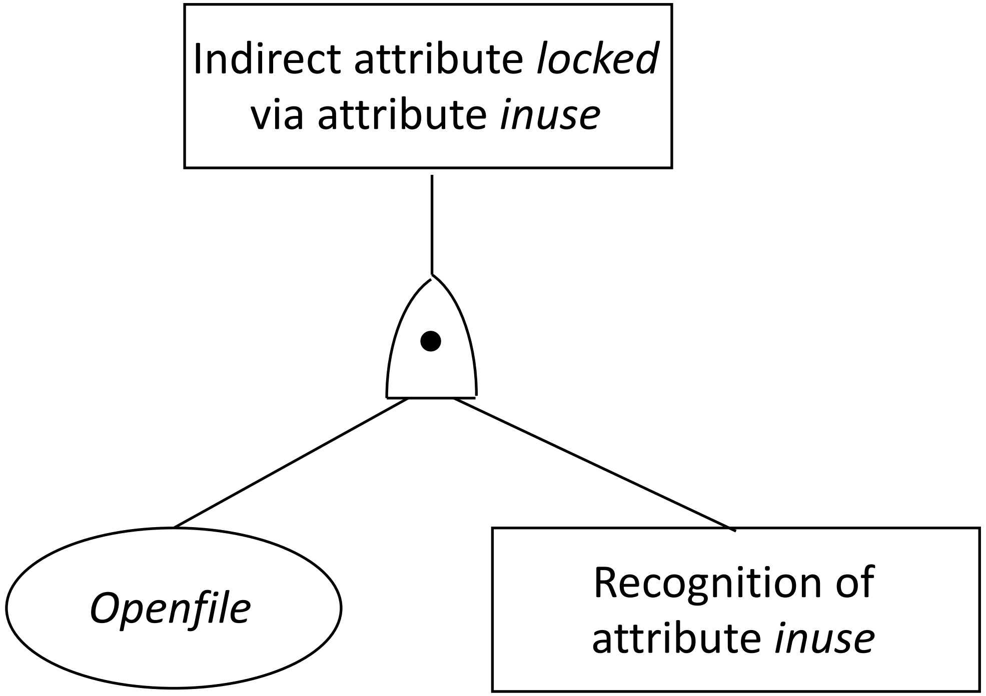




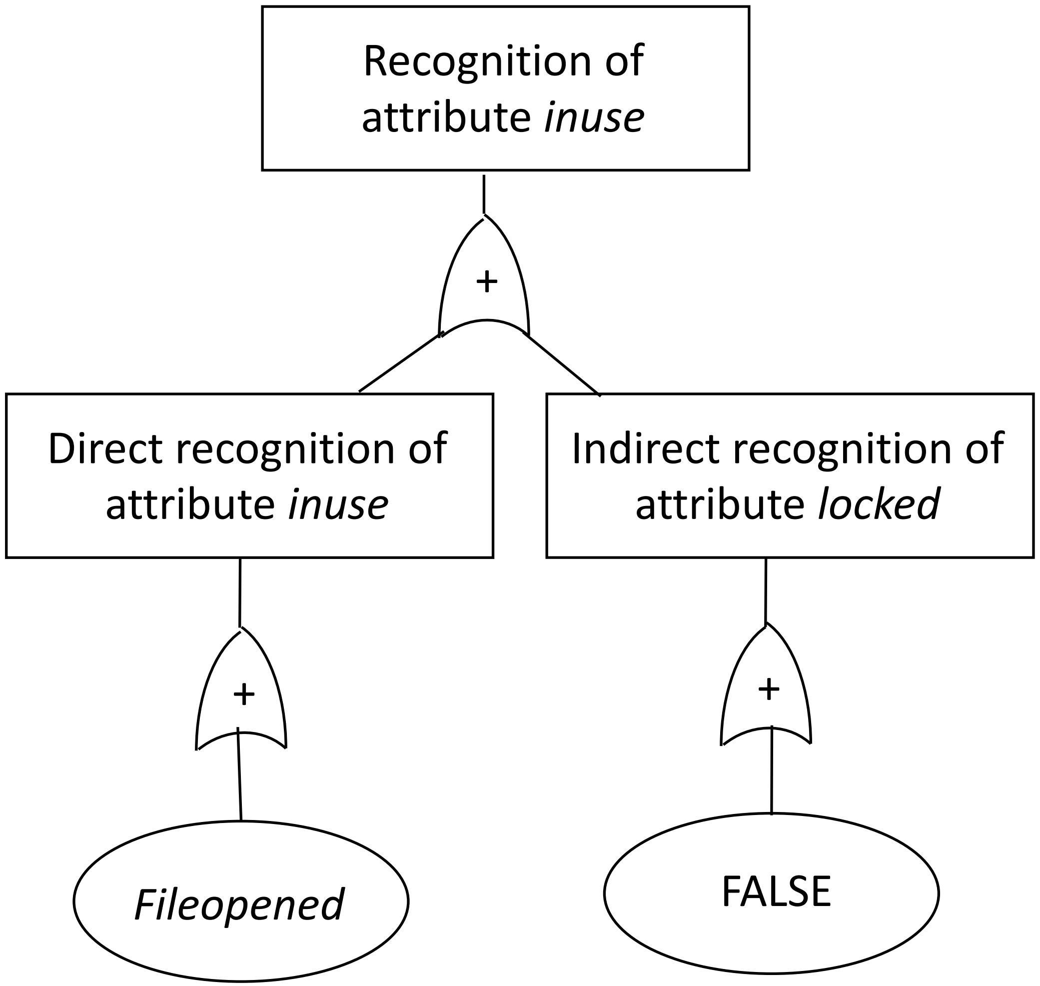
Example: Recognition Branch



Example: Indirect Branch



Example: Recognize New Goal State Branch



Example: Analysis

- Put those parts of the tree together in the obvious way
- First list: ((*Lockfile*), (*Unlockfile*))
  - As both modify attribute *locked* and lie on "modified" branch
- Second list: ((*Filelocked*), (*Openfile*, *Fileopened*))
  - From direct recognition of modification of *inuse* attribute; second, from indirect recognition of modification of attribute *locked*
- These result in 4 paths of communication:
  - *Lockfile* followed by *Filelocked*
  - *Unlockfile* followed by *Filelocked*
  - *Lockfile* followed by *Openfile*, then *Fileopened*
  - *Unlockfile* followed by *Openfile*, then *Fileopened*

Example: Analysis

- First two sequences in combination represent direct covert storage channel
  - *High* process transmits information to *Low* process by locking, unlocking file
- Last two sequences represent indirect covert storage channel
  - High process locks file to send 0, unlocks to send 1
  - Low process tries to open the file, then uses Fileopened to see if it succeeded
  - If opened, file was not locked and it’s a 1; if not opened, file is locked, and it’s a 0

Summary

- Covert flow trees, SRM come from idea that covert channels require shared resources that one process can modify and another view
- Both can be used at any point in life cycle
- Covert flow trees identify explicit sequences of operations causing information to flow
  - SRM identifies *channels*, not sequences of operations